PBH Meeting 1,
IEA "Primordial black holes from cosmological inflation"
May 2020

Lucas Pinol
With **J. Martin**, T. Papanikolaou, V. Vennin
Institut d'Astrophysique de Paris (IAP)

PREHEATING INSTABILITY

AND THE FORMATION OF PRIMORDIAL BLACK HOLES

GEODESI

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WHAT I AM NOT GOING TO TALK ABOUT

MULTI-FIELD INFLATION PHENOMENOLOGY

GEOMETRICAL ASPECTS OF CURVED FIELD SPACE (Bispectrum, single-field EFT, etc.)

[J. Fumagalli, S. Garcia-Saenz, L. Pinol, S. Renaux-Petel, J. Ronayne 2019]
[S. Garcia-Saenz, L. Pinol, S. Renaux-Petel, 2019]

MULTI-FIELD STOCHASTIC FORMALISM

EXTENSION TO CURVED FIELD SPACE (Langevin and Fokker-Planck equations, covariance, etc.)

[L. Pinol, S. Renaux-Petel, Y. Tada 2018]
[L. Pinol, S. Renaux-Petel, Y. Tada (to appear soon)]

MULTI-FIELD / MULTI-FLUID REHEATING

COUPLING SCALAR FIELDS TO COSMOLOGICAL FLUIDS (Isocurvature modes, etc.)

[J. Martin, L. Pinol (to appear some day)]

WHAT I AM GOING TO TALK ABOUT

I. THE EARLY UNIVERSE

A CONSISTENT COSMOLOGICAL STORY

II. PREHEATING INSTABILITY

SMALL SCALES GOING CRAZY

III. PBH FORMATION DURING PREHEATING

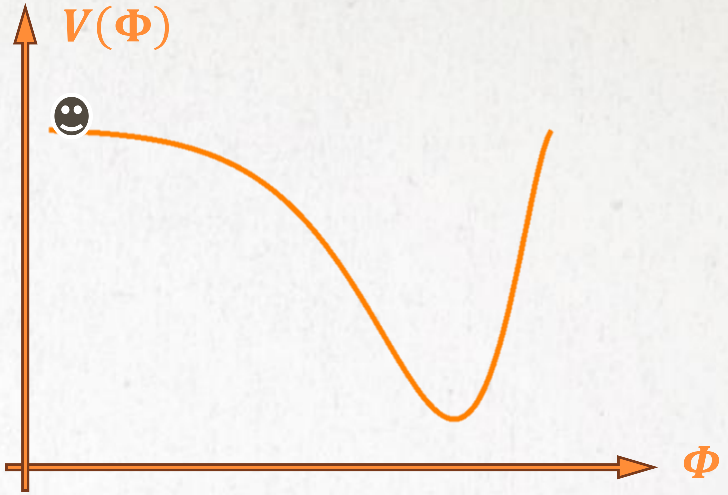
A GENERIC MECHANISM

IV. PERTURBATIVE DECAYS

WHEN PREHEATING MEETS REHEATING

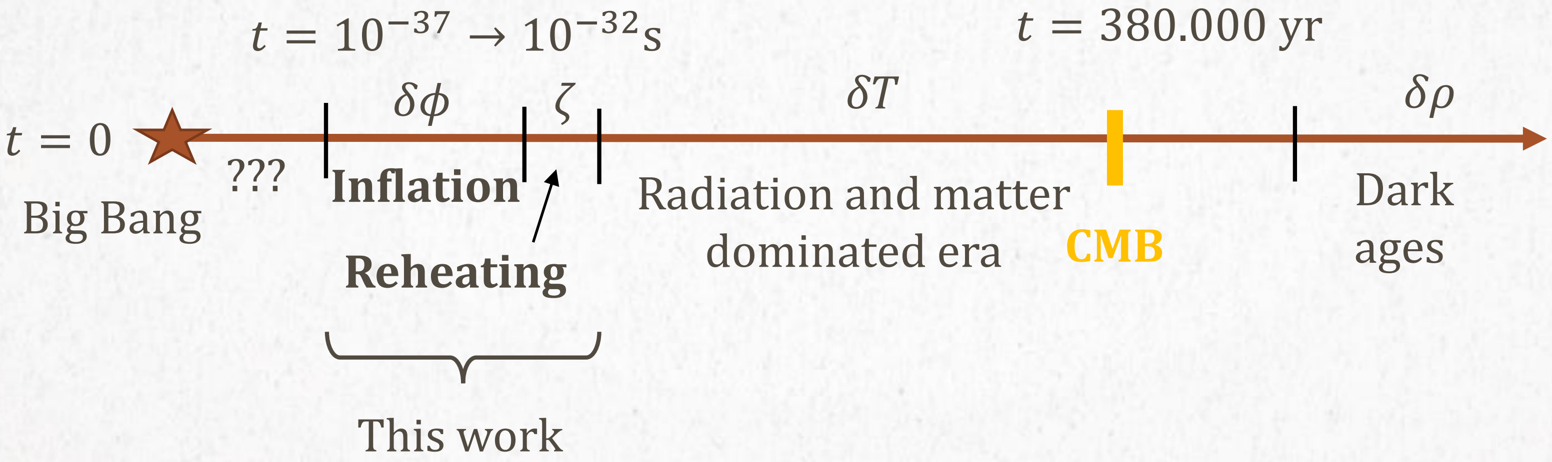
I. THE EARLY UNIVERSE

A CONSISTENT COSMOLOGICAL STORY



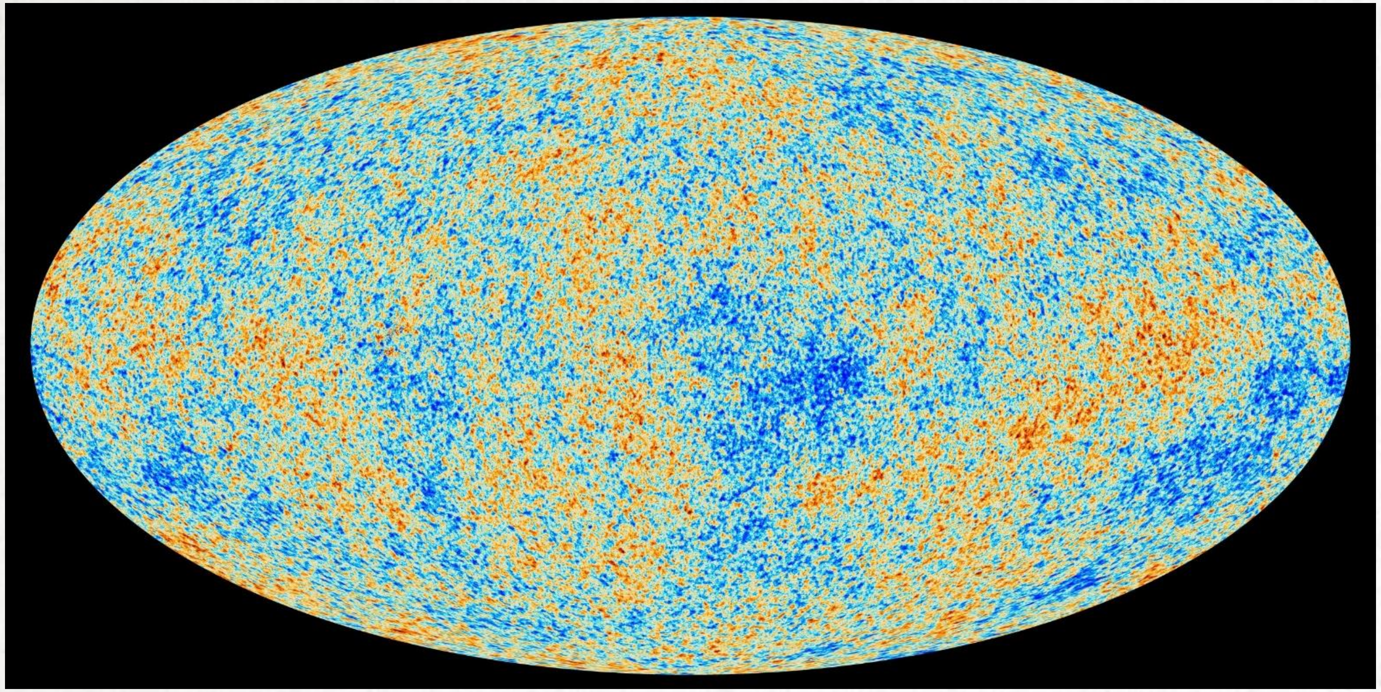
VERY BROAD PICTURE

- Cosmology: history, content and laws of the Universe
- Early Universe: before emission of the CMB



CMB is the first observational consequence of the physics in the early universe

CMB OBSERVATION MOTIVATES INFLATION



$$T \sim 2.73K \; ; \; \frac{\delta T}{T} \sim 10^{-5} \; ; \; |\Omega_k| \ll 1$$

- How is the universe so homogeneous?
  Horizon problem
- Why is the universe so spatially flat?
  Flatness problem

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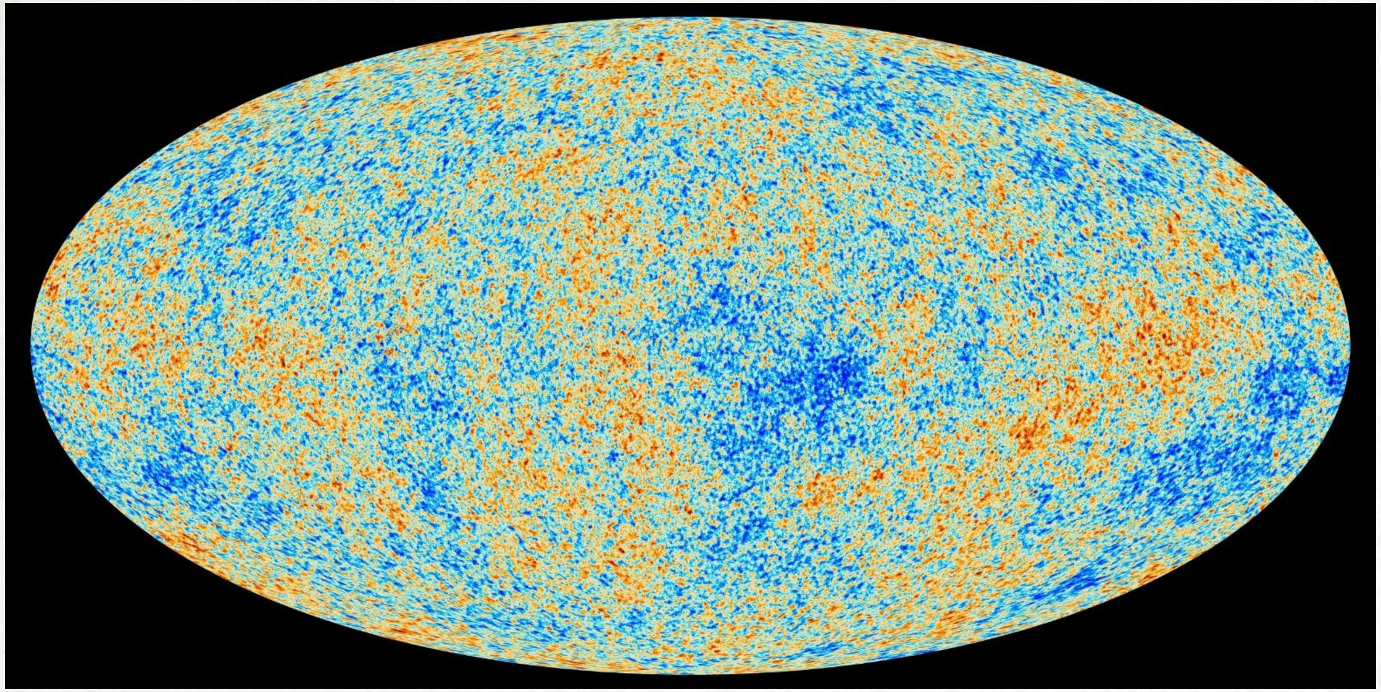

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- How is the universe so homogeneous?
  Horizon problem

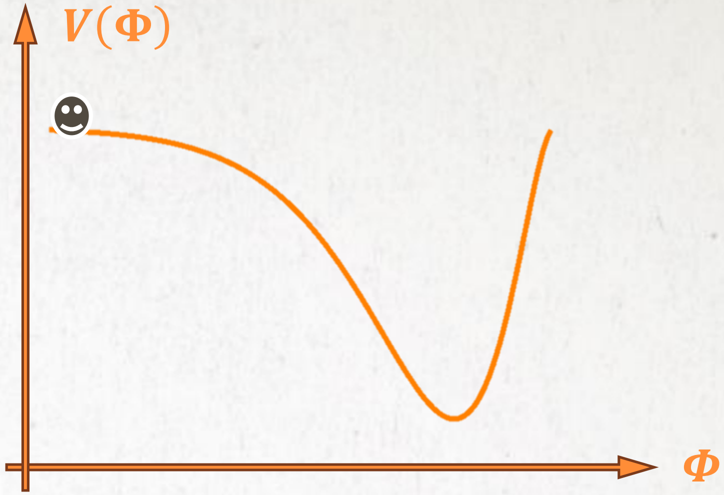
- Why is the universe so spatially flat?
  Flatness problem

Inflation, an era of accelerated expansion of the Universe, solves both the horizon and flatness problems

SLOW-ROLL SINGLE FIELD INFLATION

- Quasi de Sitter space: $\epsilon = -\frac{\dot{H}}{H^2} \ll 1\,; \eta = \frac{\dot{\epsilon}}{H\epsilon} \ll 1$

$$\Rightarrow \frac{M_p\, V'}{V} \ll 1\,; \frac{M_p^2 |V''|}{V} \ll 1$$



SLOW-ROLL SINGLE FIELD INFLATION

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From CMB observations

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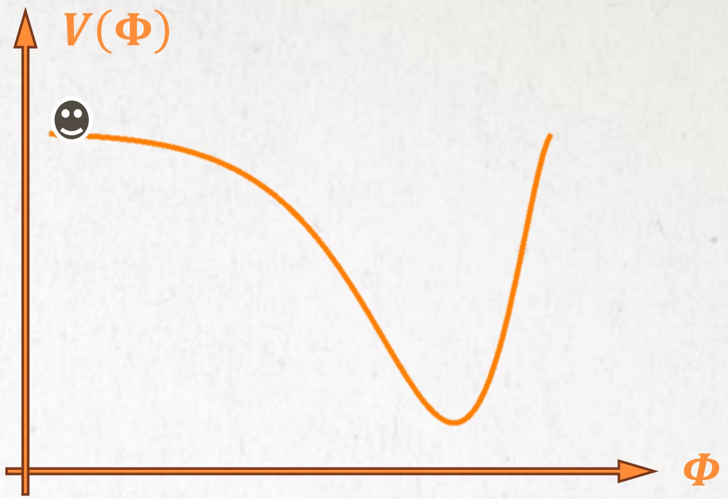

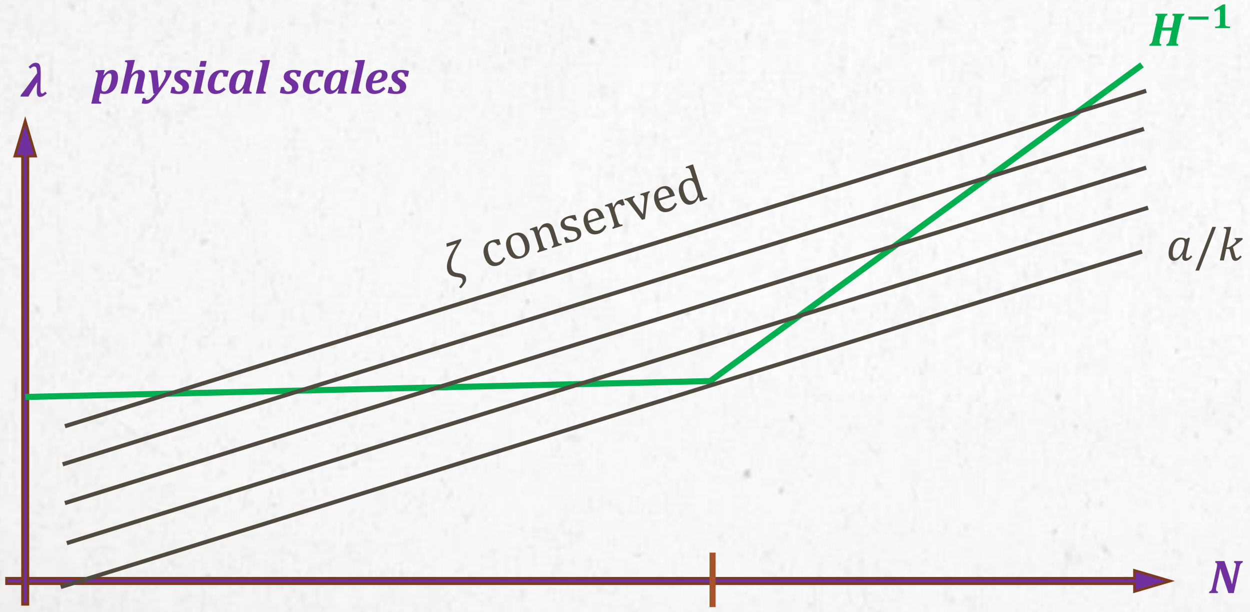

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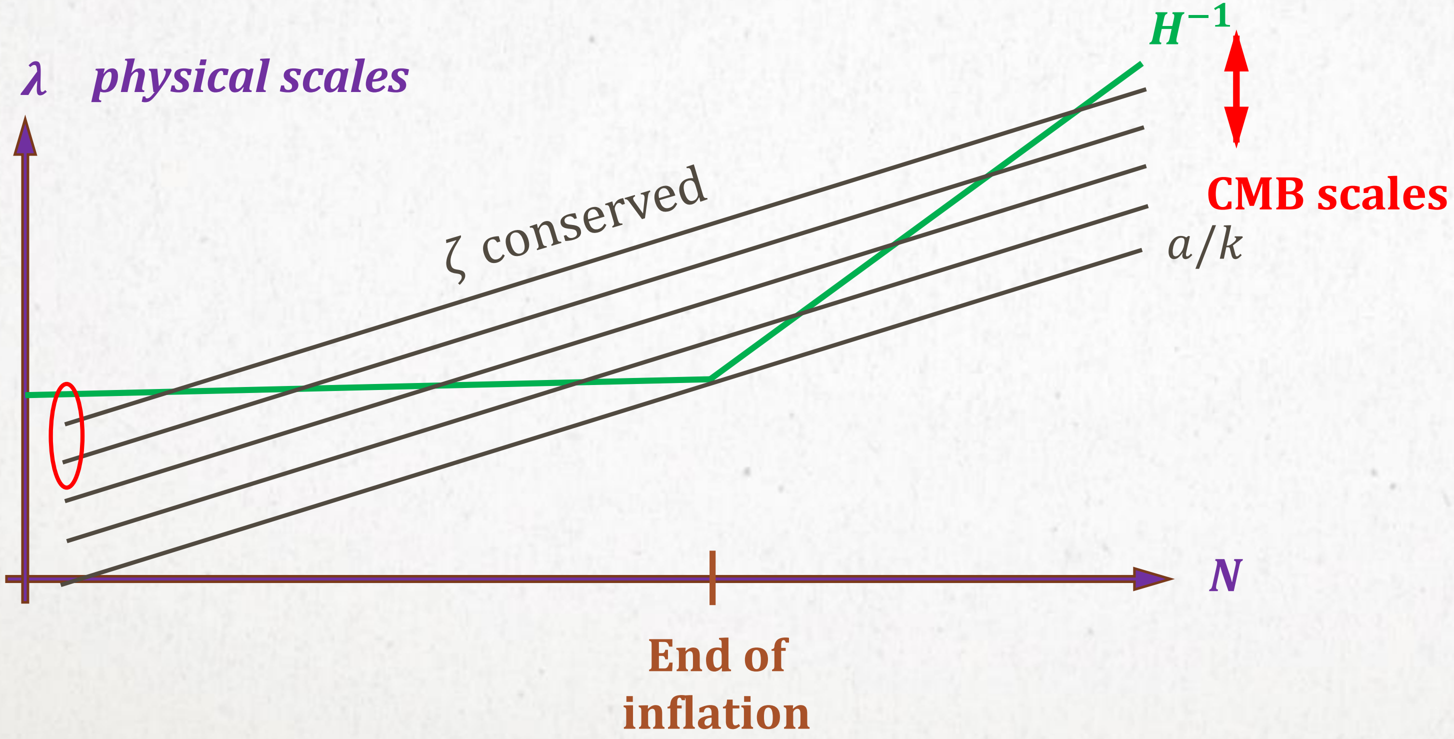

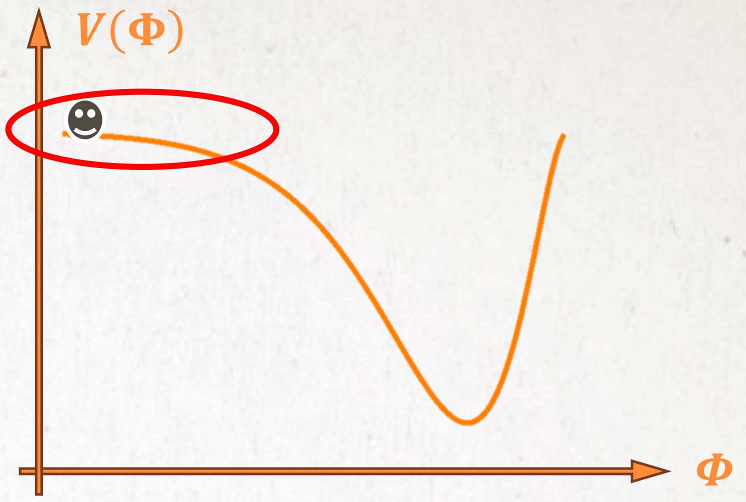

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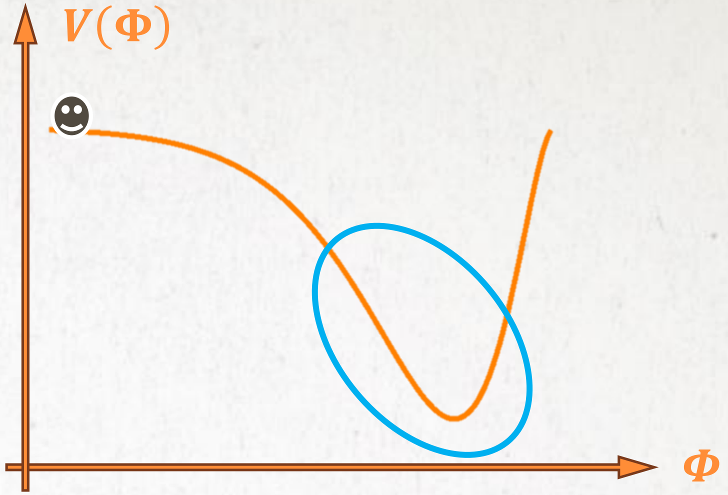
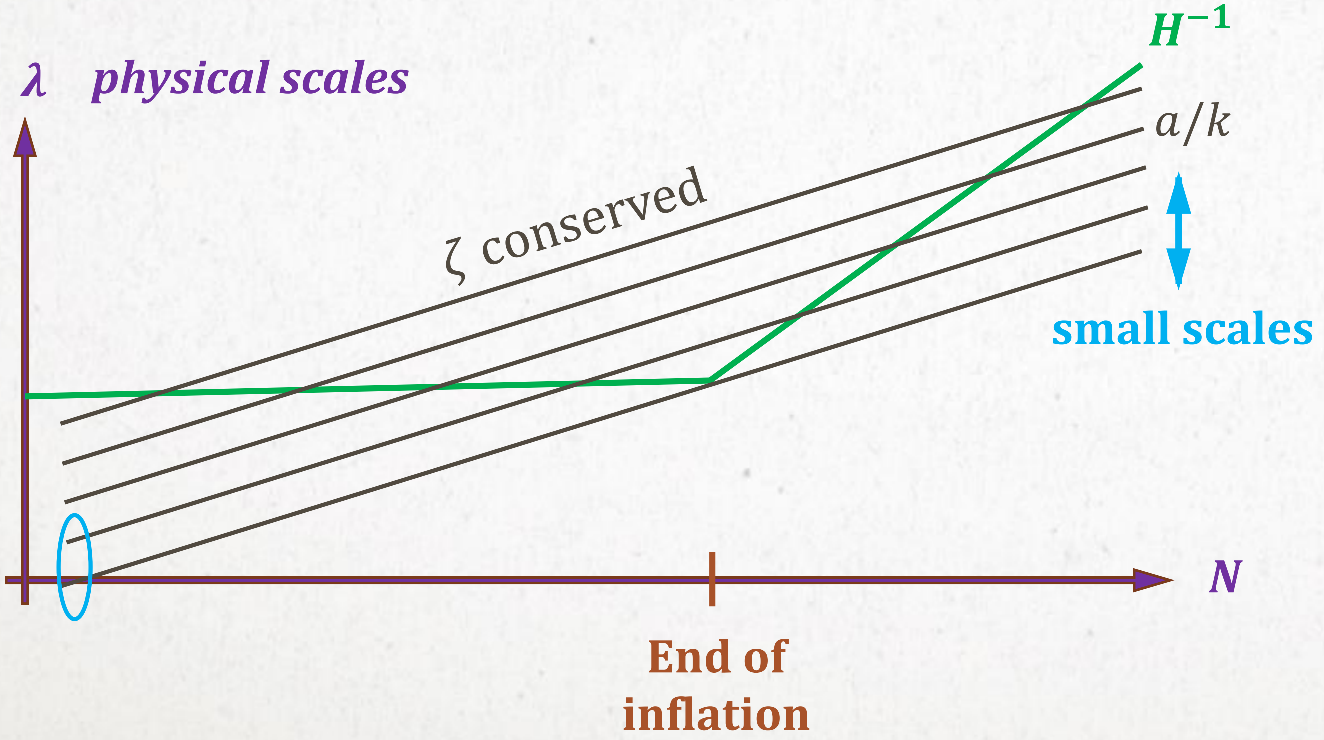




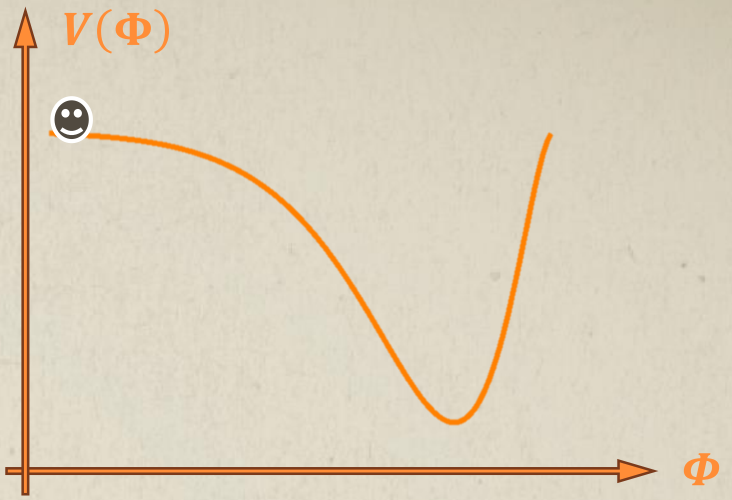
Picture both positive and negative:

- Positive: generic, CMB observables independent of the details of reheating
- Negative: no constraints on **the rest of the potential**, no further understanding

END OF INFLATION

PREHEATING AND REHEATING

- Transition between:
  - Inflation – Universe filled by scalar field(s)
  - Radiation-dominated era – Universe filled by SM particles



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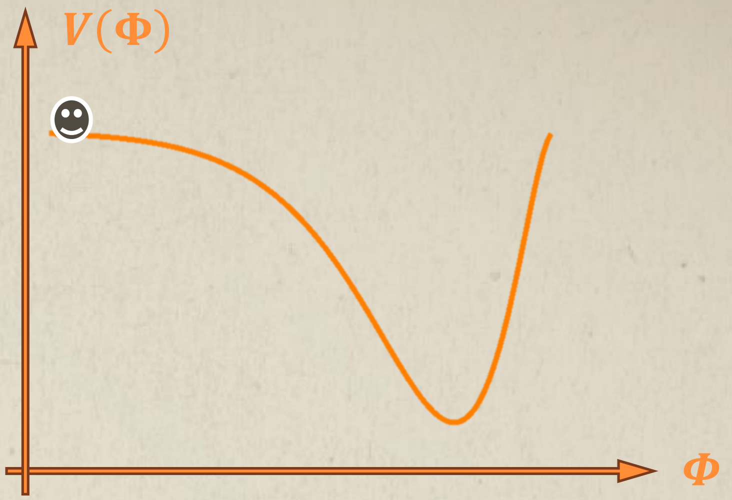

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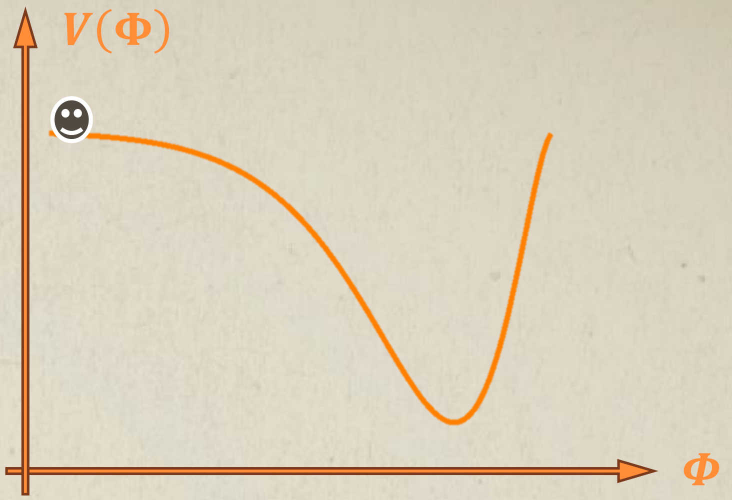
- But not enough to disappear + also need to produce SM particles

Perturbative reheating

$$\ddot{\phi} + 3H\,\dot{\phi}\,\boxed{+\,\Gamma\dot{\phi}} + V'(\phi) = 0$$



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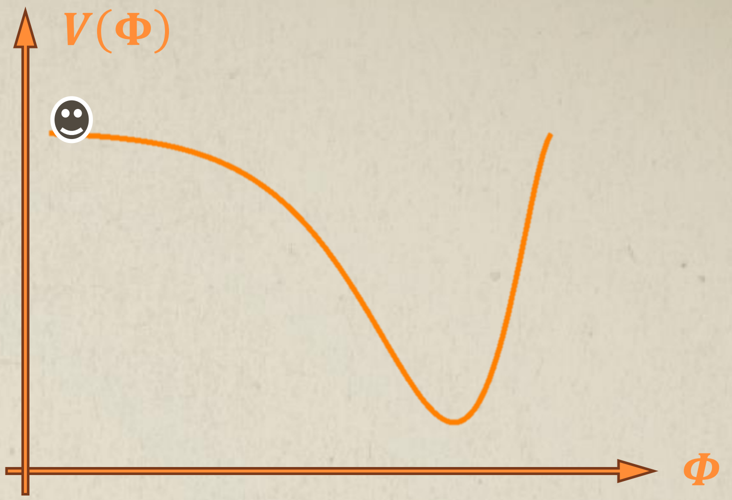
Perturbative reheating

$$\ddot{\phi} + 3H\,\dot{\phi} \boxed{+\,\Gamma\dot{\phi}} + V'(\phi) = 0$$

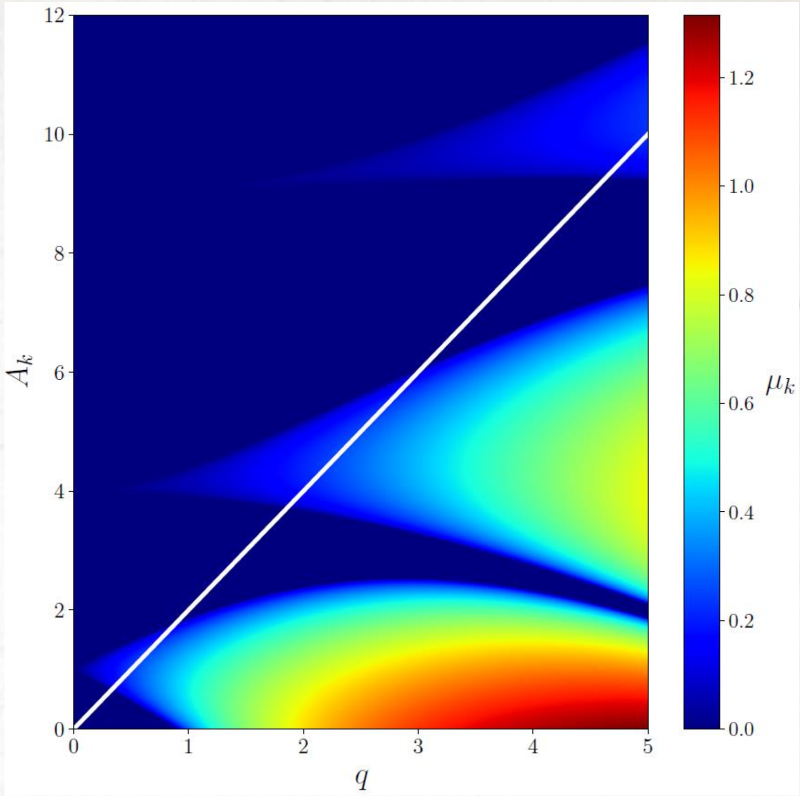
- Few strategies to get this equation:
  - Add a decay term phenomenologically (what about perturbations?)
  - Coupling the inflaton to another scalar field believed to be a « proxy » for SM particles, study this decay
  - Coupling the inflaton directly to a cosmological fluid like radiation



II. PREHEATING INSTABILITY

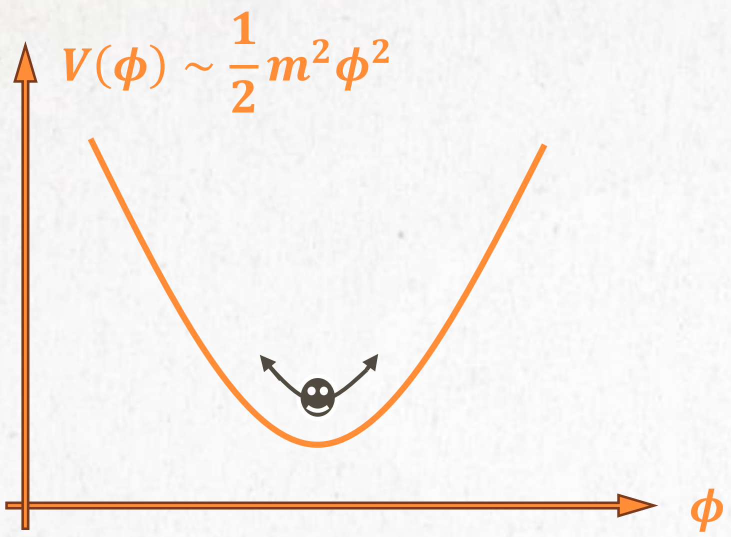
SMALL SCALES GOING CRAZY

[K. Jedamzik, M. Lemoine, J. Martin 2010]



PREHEATING

ALL ABOUT OSCILLATIONS



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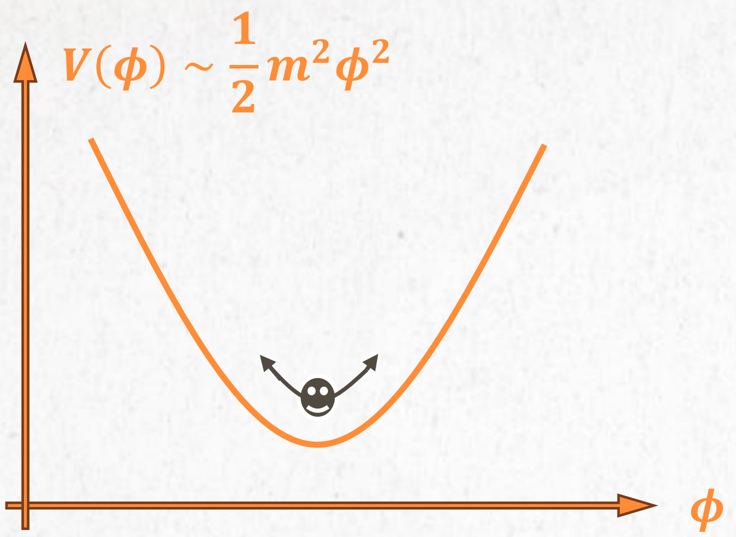


Background: coherent oscillations of the scalar field

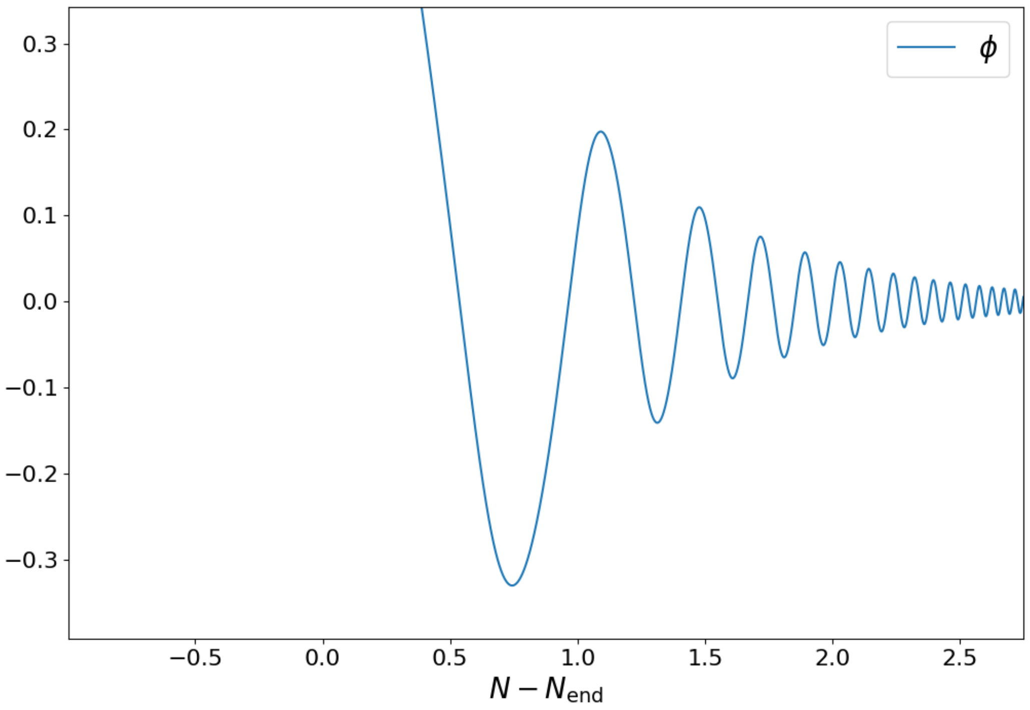
$$\phi(t) \simeq \phi_{\text{end}} \left(\frac{a_{\text{end}}}{a}\right)^{3/2} \sin(mt)$$

Overall amplitude
of the oscillations

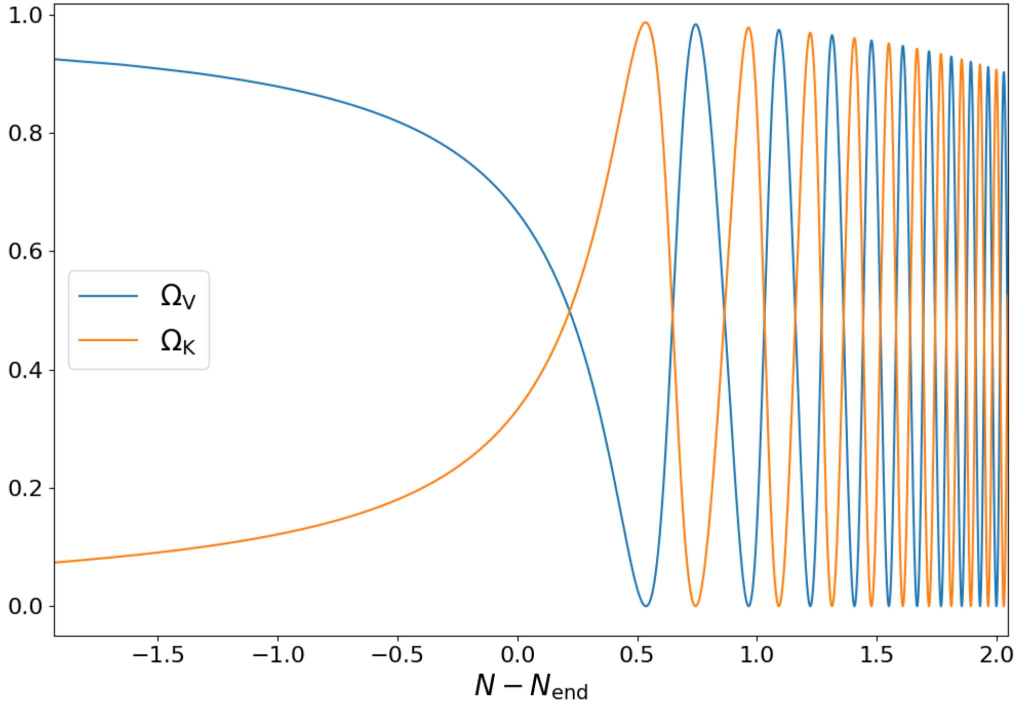
$\rho_\phi \sim a^{-3}$ redshifts as
pressureless matter

PREHEATING

ALL ABOUT OSCILLATIONS



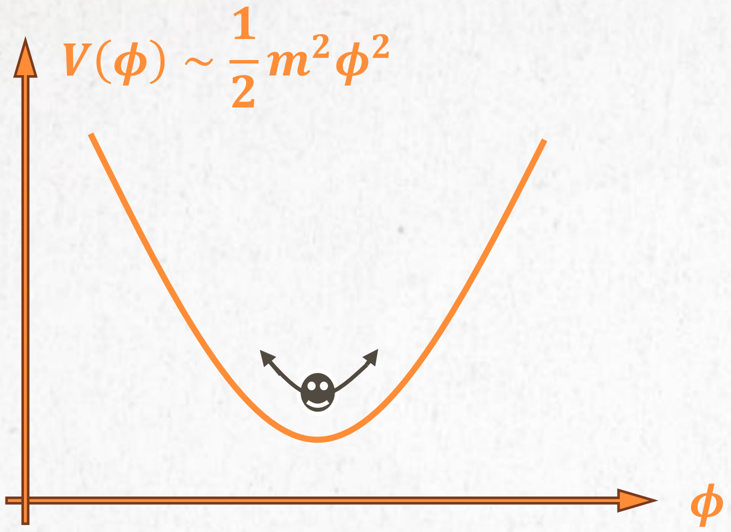
Damped oscillations



Equipartition of energy during oscillations

METRIC PREHEATING

ALL ABOUT OSCILLATIONS



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Perturbations:

$\chi_k = \sqrt{a}\boldsymbol{v_k}$ verifies a Mathieu equation

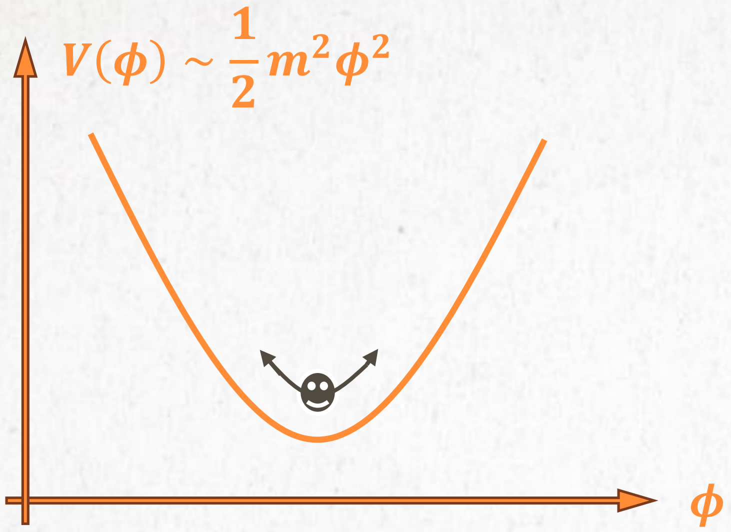
Sasaki-Mukhanov variable

$$\frac{d^2\chi_k}{dz^2} + (A_k - 2q\cos(2z))\chi_k = 0$$

with
$$\begin{cases} A_k = 1 + \dfrac{k^2}{m^2 a^2} \\[2ex] q = \dfrac{\sqrt{6}}{2} \dfrac{\phi_{\text{end}}}{M_p} \left(\dfrac{a_{\text{end}}}{a}\right)^{3/2} \end{cases}$$

METRIC PREHEATING

ALL ABOUT OSCILLATIONS



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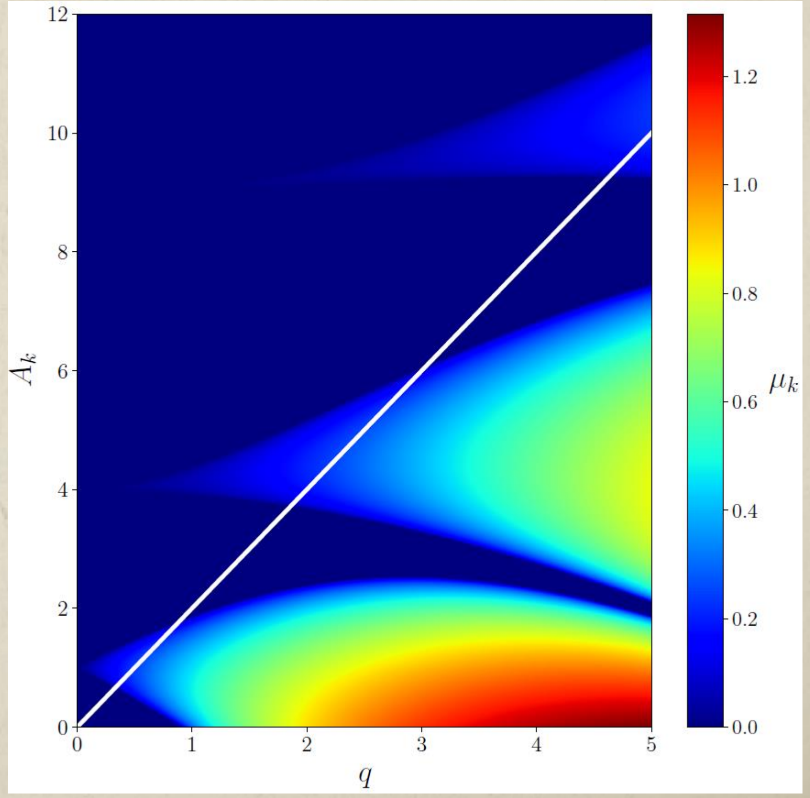
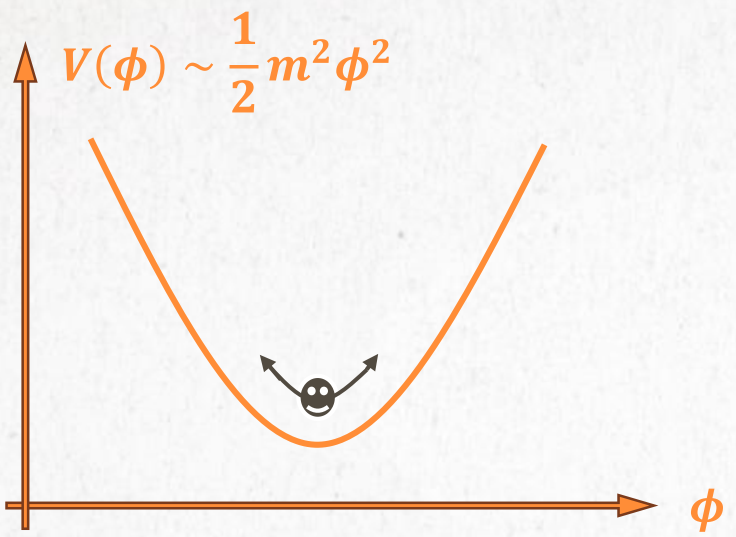


Instability bands of the Mathieu equation

METRIC PREHEATING

ALL ABOUT OSCILLATIONS



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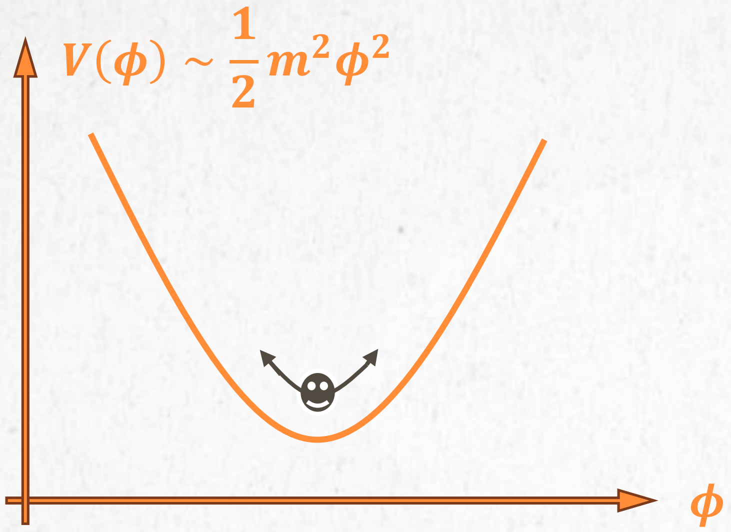
Dynamically, $\begin{cases} A_k \to 1 \\ q \to 0 \end{cases}$

METRIC PREHEATING

ALL ABOUT OSCILLATIONS



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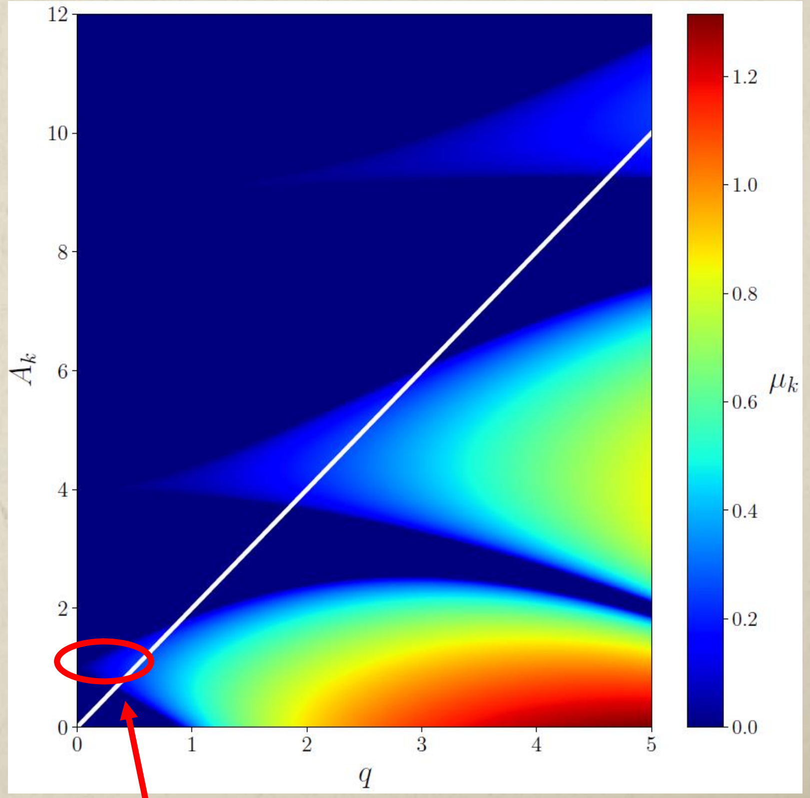


First instability band

METRIC PREHEATING

INSTABILITY BAND FOR LINEAR PERTURBATIONS

Modes are in the instability band if:

$$A_k < 1 + q$$

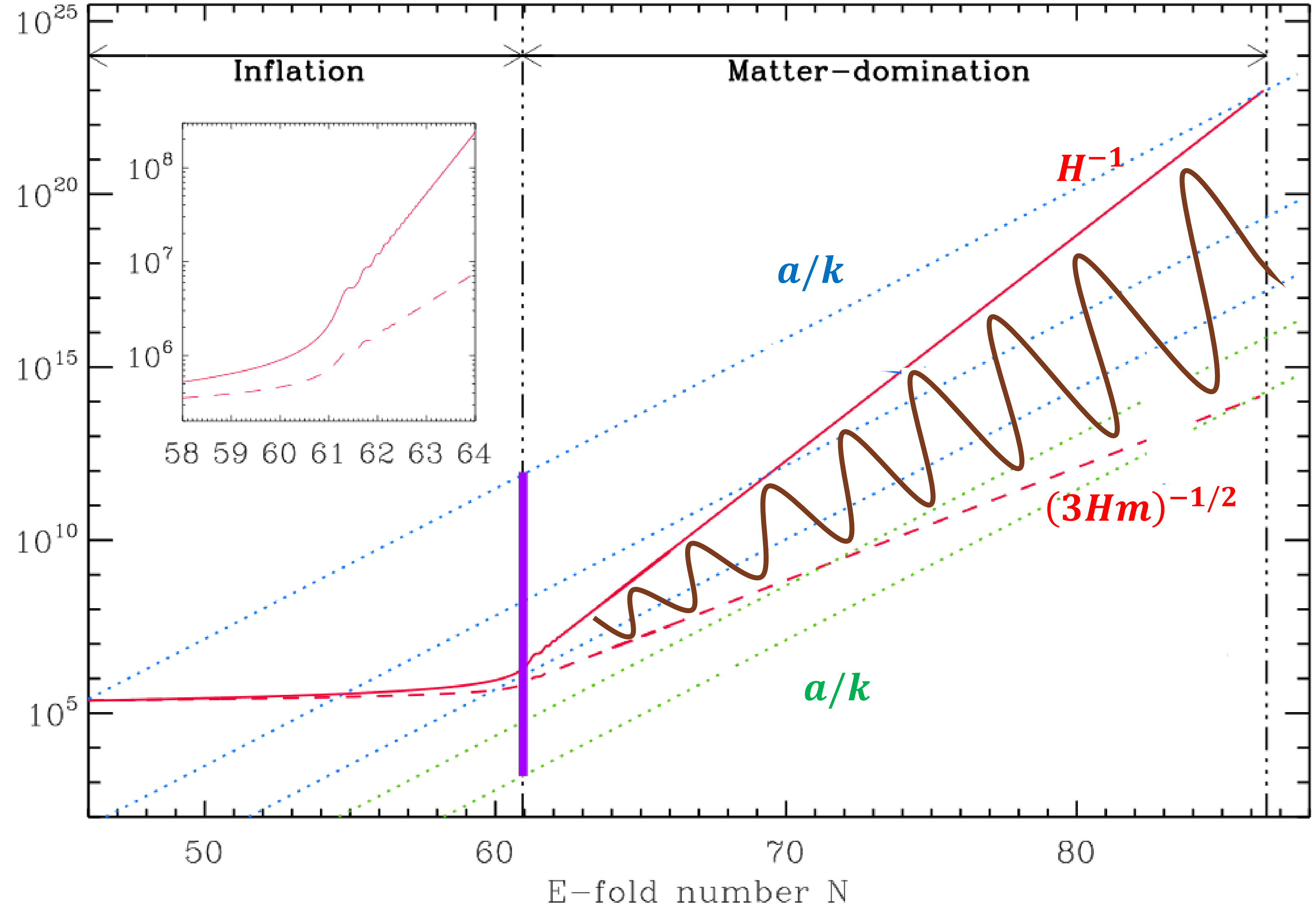
$$\Downarrow$$

$$\sqrt{3Hm} < k/a < H$$

METRIC PREHEATING

INSTABILITY BAND FOR LINEAR PERTURBATIONS

[K. Jedamzik, M. Lemoine, J. Martin 2010]



Modes are in the instability band if:

$$\sqrt{3Hm} < k/a < H$$

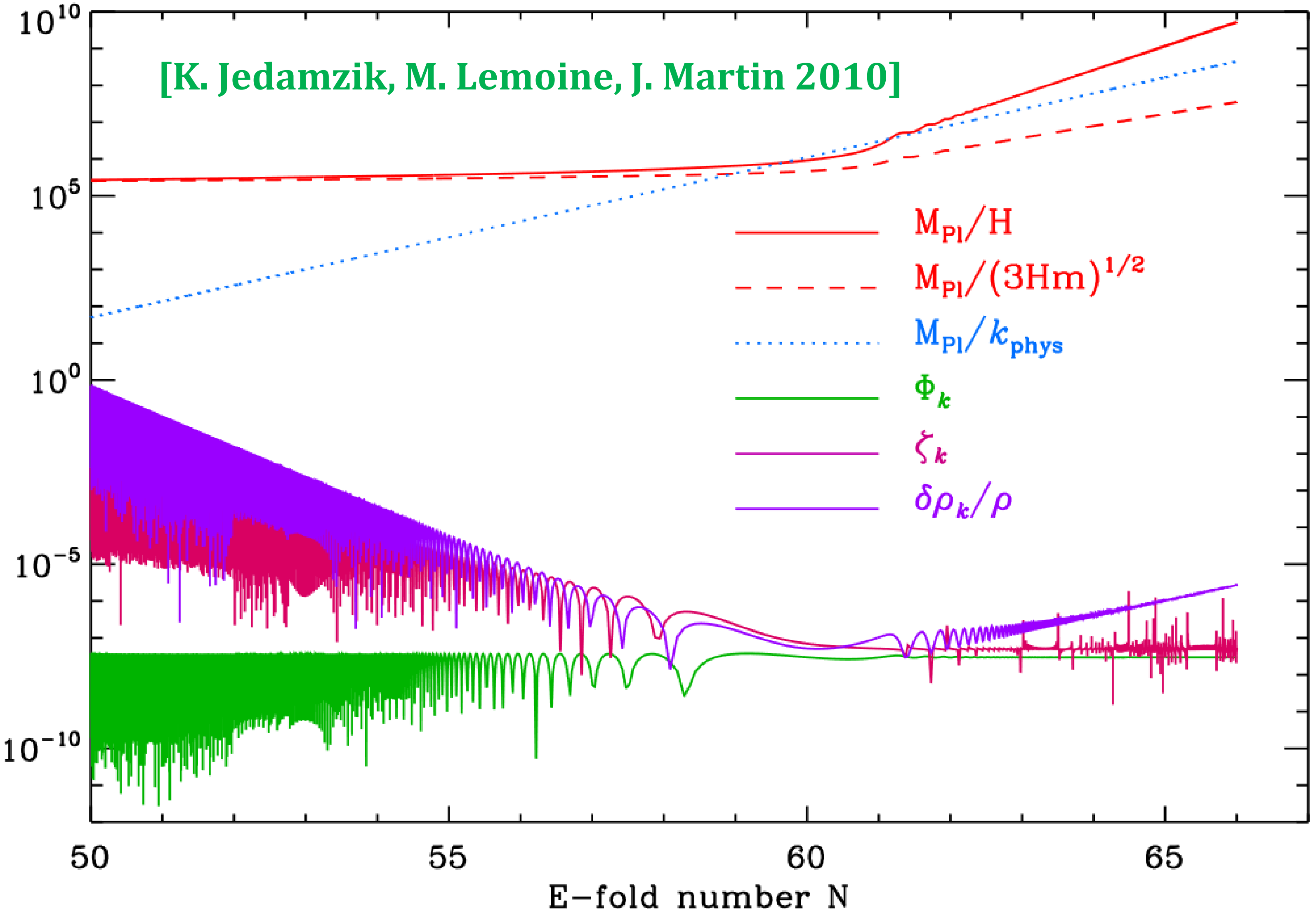
Modes can enter:

- **From above** as $H^{-1} \sim a^{3/2}$
- **From below** as $(3Hm)^{-1/2} \sim a^{3/4}$

Then they stay in the band
(until oscillations stop)

METRIC PREHEATING

INSTABILITY BAND FOR LINEAR PERTURBATIONS



Φ_k is constant

ζ_k is constant

$\delta_k = \frac{\delta\rho_\phi^k}{\rho_\phi}$ is exponentially growing

METRIC PREHEATING

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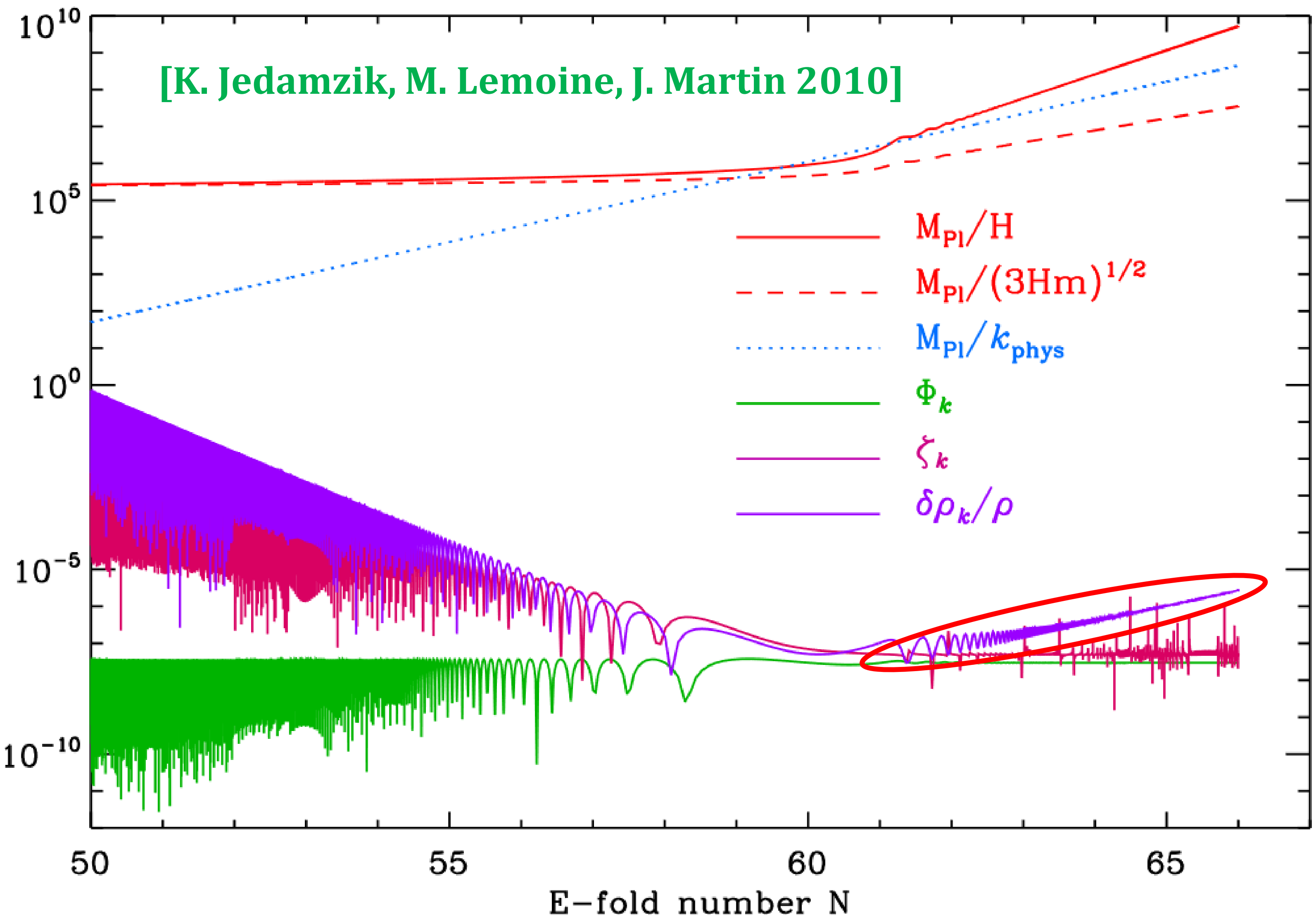

Scalar power spectrum peaked on small scales

- Secondary, induced GWs
[K. Jedamzik, M. Lemoine, J. Martin 2010]

- Primordial black holes
[J. Martin, T. Papanikolaou, V. Vennin 2019]

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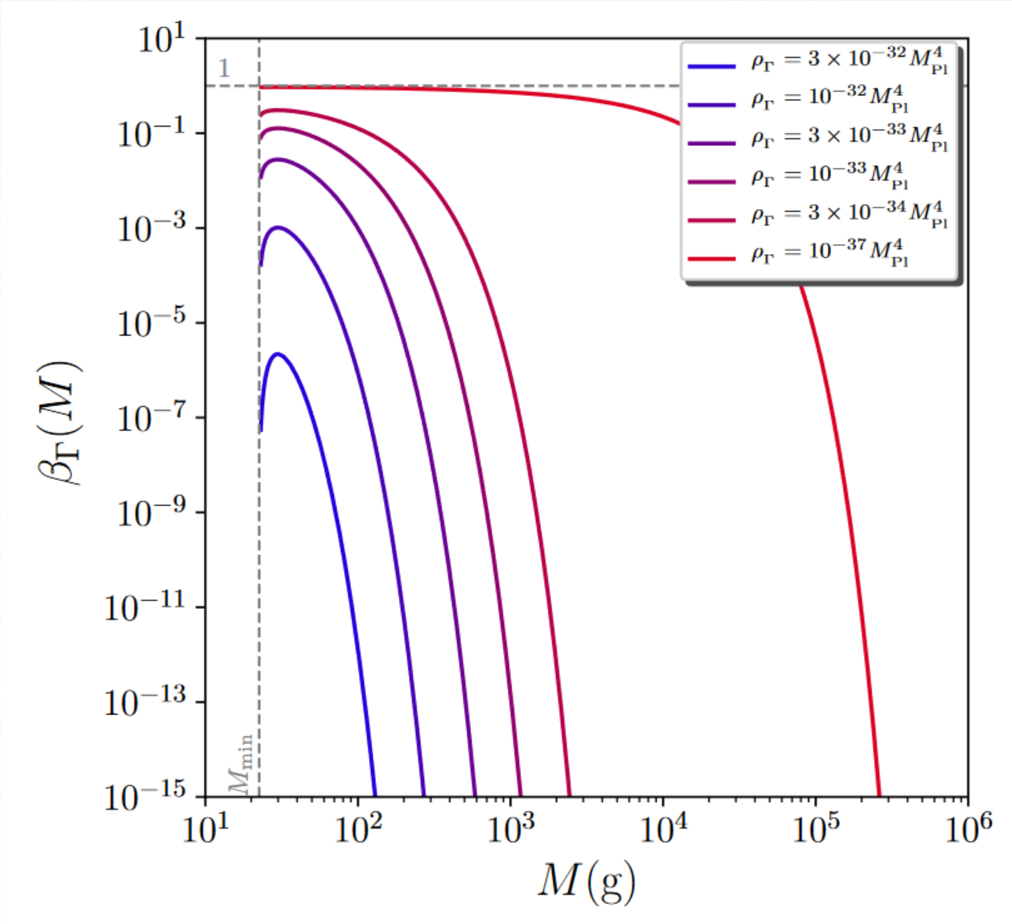
III. PBH FORMATION DURING PREHATING

A GENERIC MECHANISM

[J. Martin, T. Papanikolaou, V. Vennin 2019]

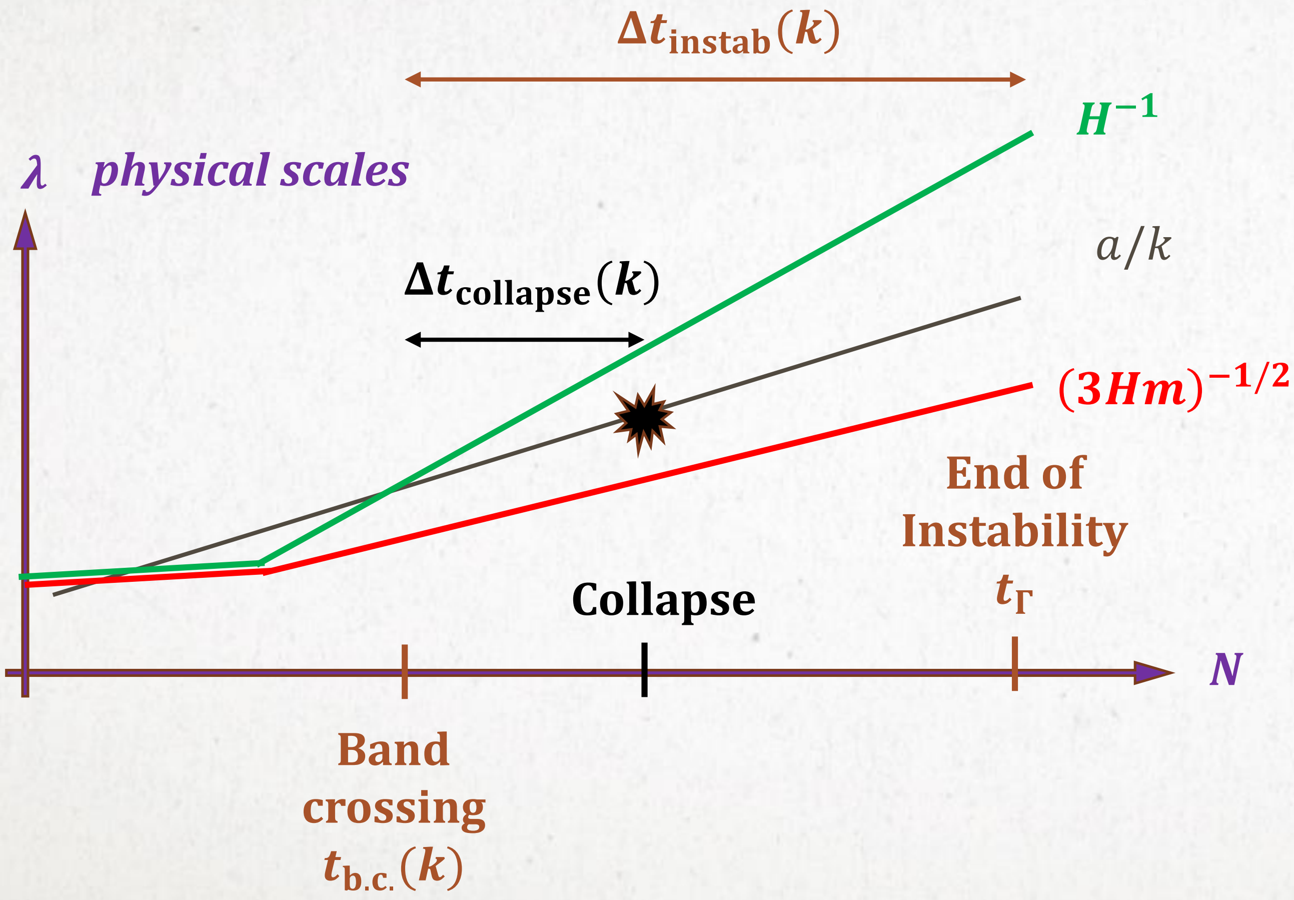


PBH FORMATION

FORMATION CRITERION

$$\Delta t_{\text{collapse}}(k) = \frac{\pi}{\left(H\, \delta_k^{3/2}\right)\big|_{t_{\text{b.c.}}(k)}}$$

[S. M. C. V. Goncalves 2000]



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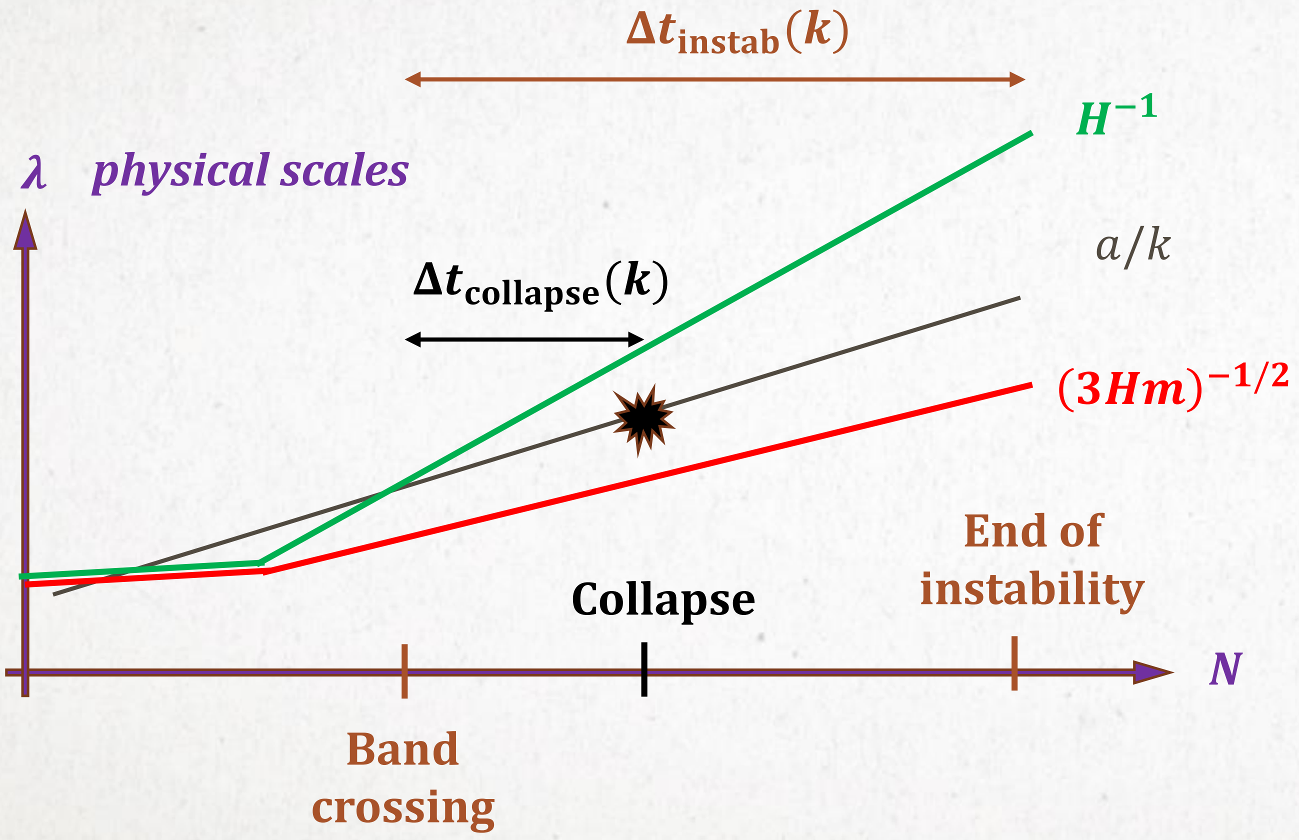
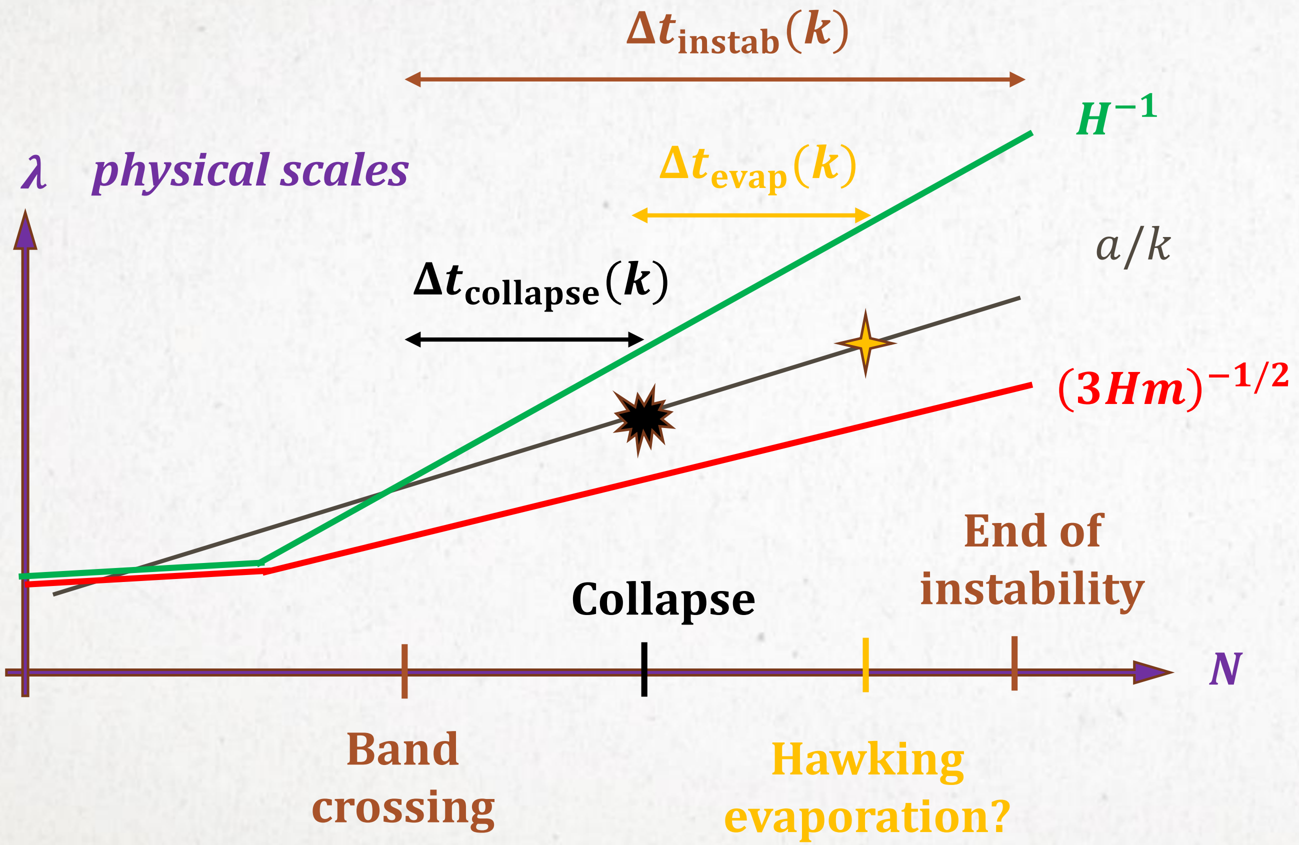


Criterion for PBH formation:

$$\Delta t_{\text{collapse}} < \Delta t_{\text{instab}}$$

PBH FORMATION

SURVIVAL CRITERION

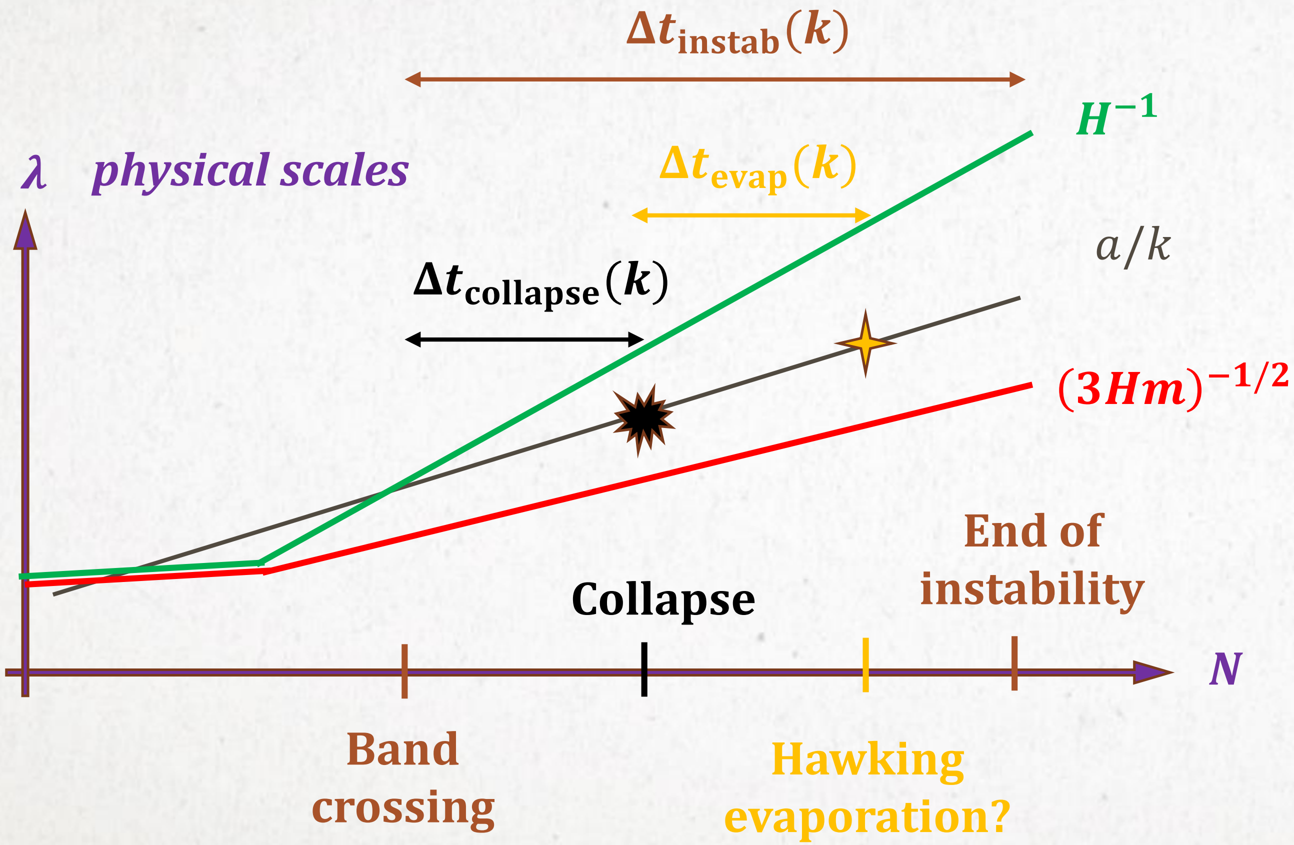


$$\Delta t_{\rm evap}(k) = \frac{10240}{g}\frac{M(k)^3}{M_{\rm p}^4}$$

[S. Hawking 1974]

PBH FORMATION

SURVIVAL CRITERION



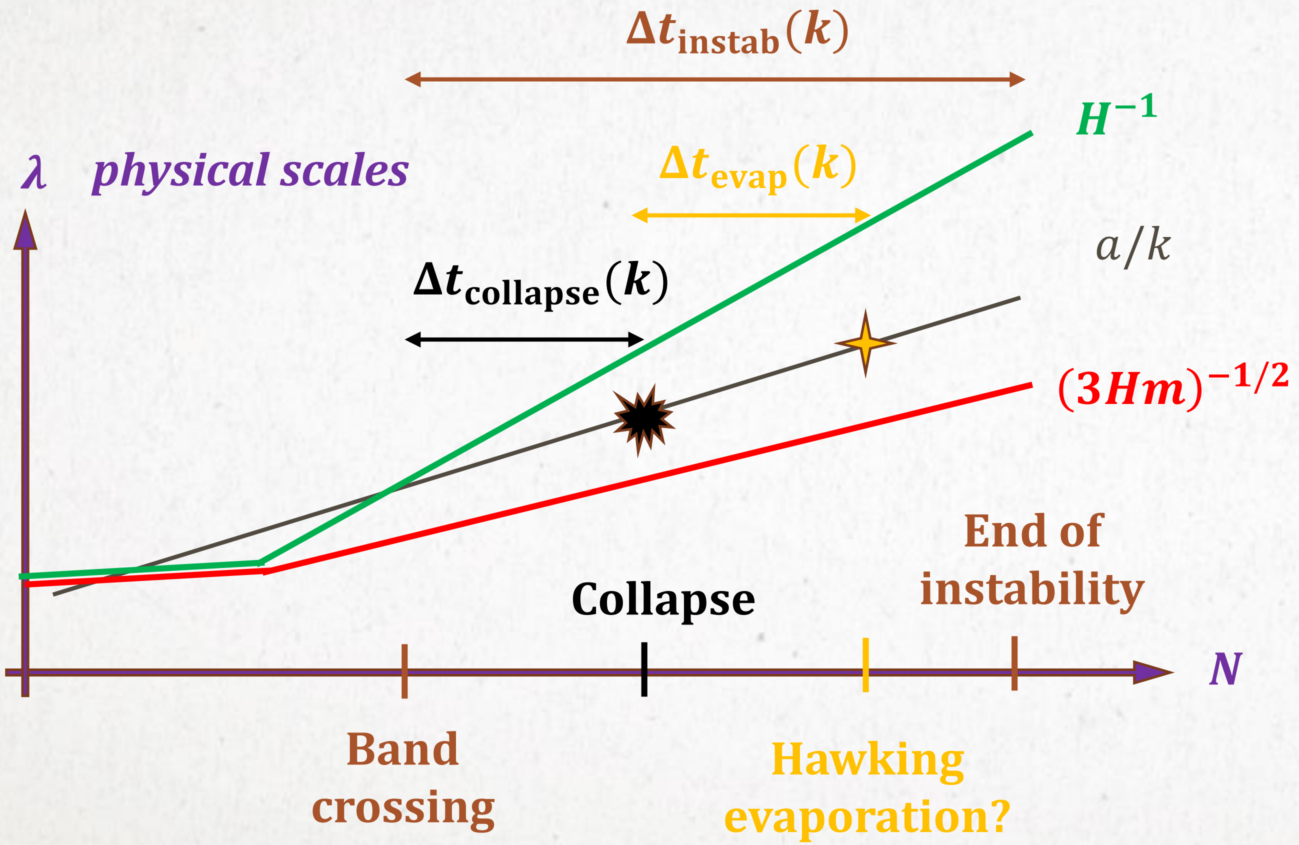
$$\Delta t_{\mathrm{evap}}(k) = \frac{10240}{g}\frac{M(k)^3}{M_{\mathrm{p}}^4}$$

Criterion for PBH at the end of the instability:

$$\Delta t_{\mathrm{collapse}} + \Delta t_{\mathrm{evap}} > \Delta t_{\mathrm{instab}}$$

PBH FORMATION

SURVIVAL CRITERION



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PBH FORMATION

MASS FRACTION AT THE END OF THE INSTABILITY

$$\delta_c(k) < \delta_k < \delta_{\max}(k)$$

Formation

- Survival
- Perturbativity $\left(\delta_k|_{t_{\text{b.c.}}(k)} < 1\right)$

$$\beta(M(k), t_\Gamma) = 2\int_{\delta_c(k)}^{\delta_{\max}(k)} P(\delta)\mathrm{d}\,\delta$$

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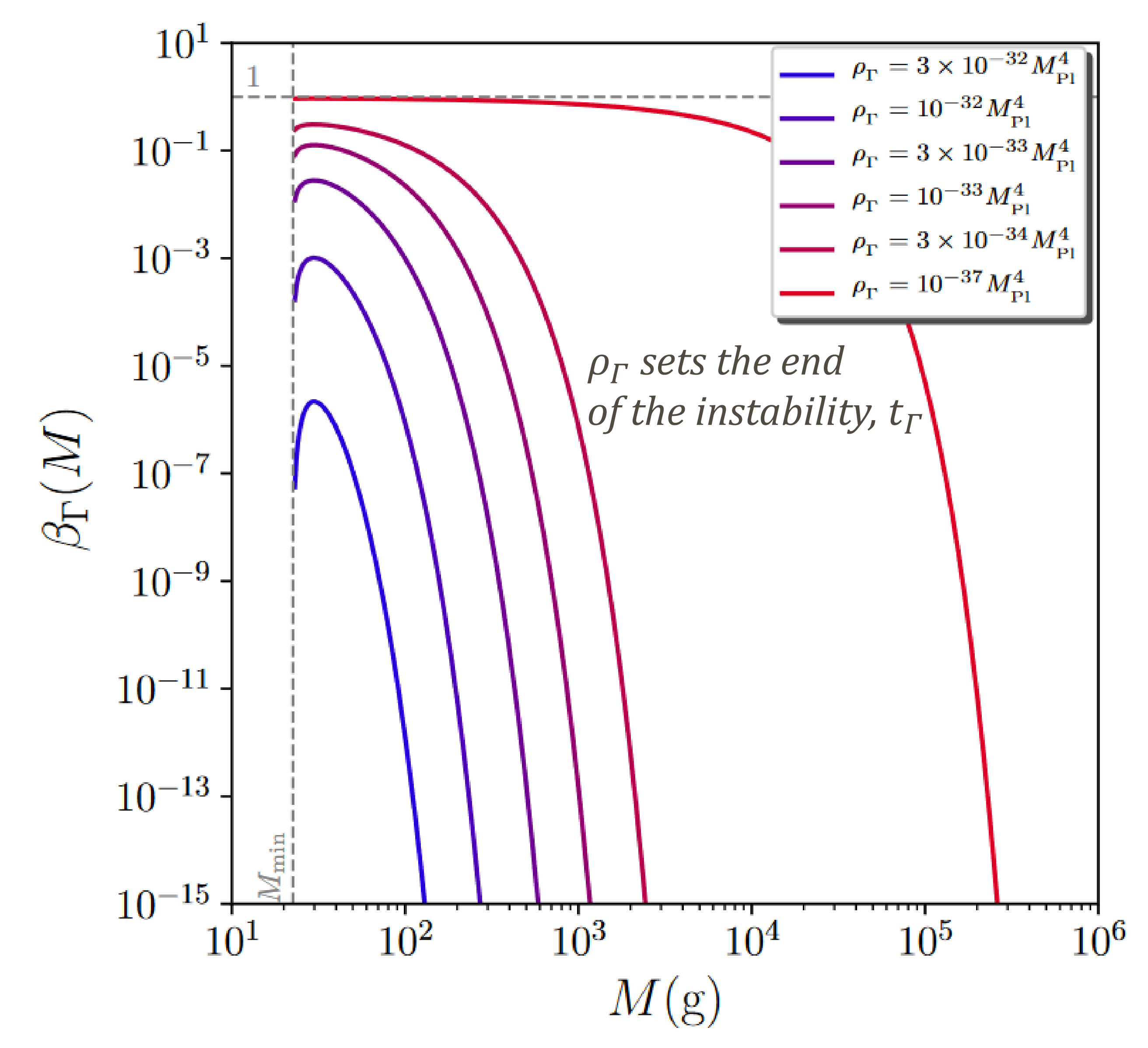
The longer the instability:
the more PBHs
the more massive they are



PBH FORMATION

OVERPRODUCTION AND CONSTRAINTS FROM BBN

Unphysical of course!

- If the instability lasts long enough, $\Omega_{\mathrm{PBH}} > 1$
  - ➢ When large scales collapse, they can already include smaller black holes: counted twice
  - ➢ When PBHs are copiously produced, they modify the background dynamics: premature ending

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- Evolving the mass fraction to BBN
  - Redshift, Hawking evaporation, etc.
  - If too many black holes survive, constrains parameter space

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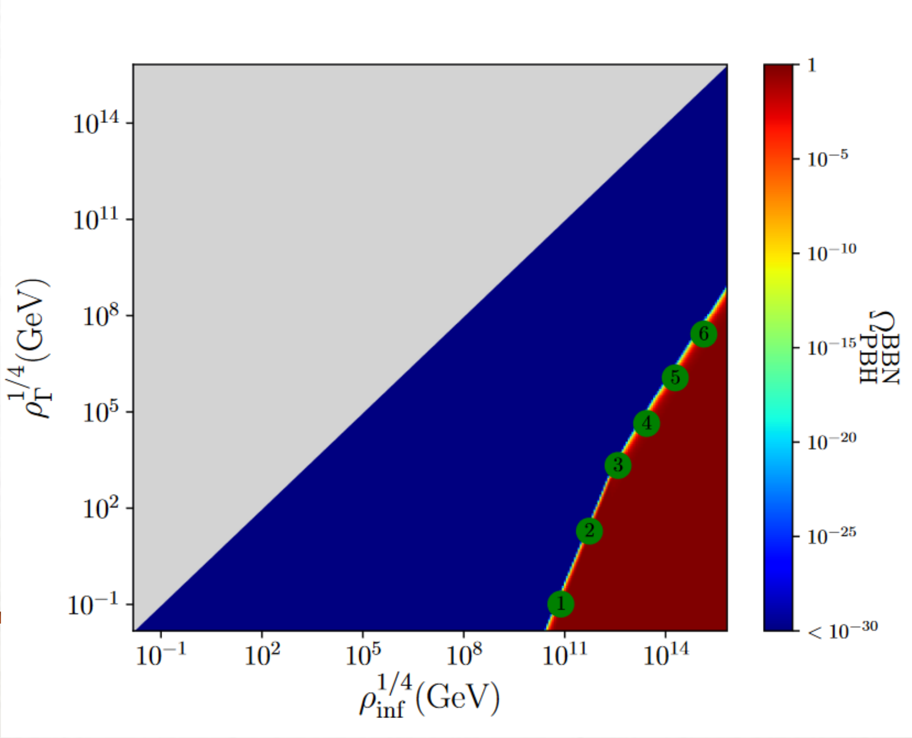
Here, constraints on the duration of the instability



PBH FORMATION

AN EVER-LASTING INSTABILITY?

How does the instability stop?!

In this work, the end was just parametrized by the time t_Γ, or ρ_Γ

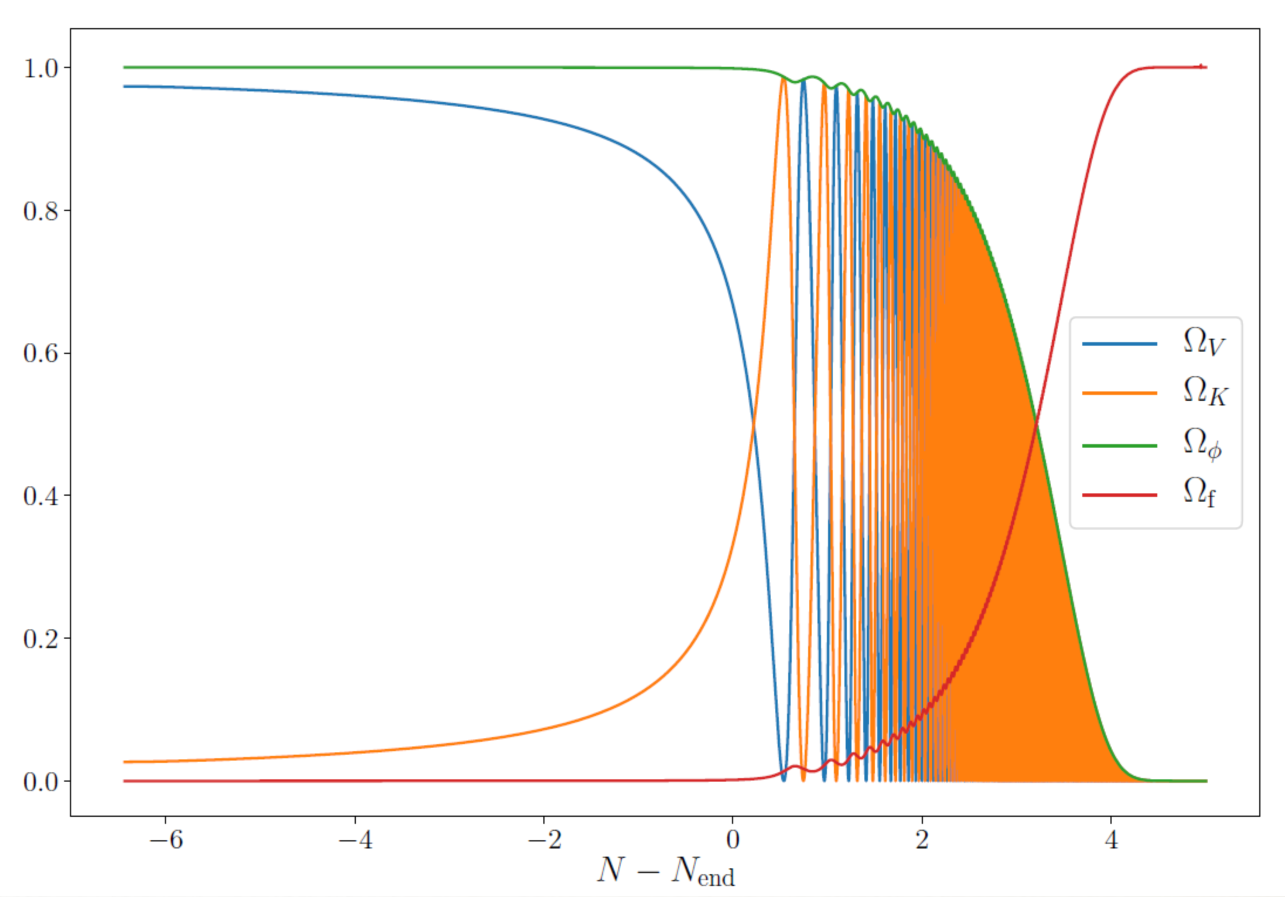
Realistically, couplings to SM+DM fields (reheating)

Could it actually spoil the whole instability?

IV. PERTURBATIVE DECAYS

WHEN PREHEATING MEETS REHEATING

[J. Martin, T. Papanikolaou, L. Pinol, V. Vennin 2020]



COUPLING THE INFLATON

TO ANOTHER SCALAR FIELD

[L Kofman, A. Linde, A. Starobinsky 1997]

- This other scalar then decays in SM+DM particles
- Microphysics easy to discuss as only scalar fields: $\mathcal{L}_{\text{int}} = -2g^2\sigma\phi\chi^2$

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- Effectively modifies the e.o.m. for ϕ as: $\ddot{\phi} + 3H\,\dot{\phi} \boxed{+ \Gamma\dot{\phi}} + V'(\phi) = 0,$

With $\Gamma = \dfrac{g^4\sigma^2}{2\pi m}$

Additional damping that ends the oscillating phase

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- Effectively modifies the e.o.m. for ϕ as: $\ddot{\phi} + 3H\,\dot{\phi} + \Gamma\dot{\phi} + V'(\phi) = 0,$
- Both perturbative and <u>non-perturbative</u> effects: $\frac{d^2X}{dz^2} + (A - 2q\cos(2z))X = 0$

  « usual » preheating

With $X = a^{3/2}\chi$

Copious production of χ particles: Bose enhancement

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With $\mathrm{X} = a^{3/2}\chi$

Very insteresting physics

But does not lead to radiation-dominated era

At least not with photons, etc.

COUPLING THE INFLATON

TO A COSMOLOGICAL FLUID

- 1 scalar field = 2 **interacting** cosmological fluids

[K. Malik, D.Wands 2008]

Cosmological fluid

Constant equation of state $w = P/\rho$

Remember for a single scalar-field

$$w = \frac{P}{\rho} = \frac{E_k - E_p}{E_k + E_p} \left(= \frac{\rho_K w_K + \rho_V w_V}{\rho_k + \rho_V} \right)$$

As if the universe was filled by two cosmological fluids with:

$\rho_K = E_k$; $w_K = 1$: Kinetic fluid
$\rho_V = E_p$; $w_V = -1$: Potential fluid

COUPLING THE INFLATON

TO A COSMOLOGICAL FLUID

- 1 scalar field = 2 interacting cosmological fluids

- Interacting cosmological fluids are characterized by:

$$T_{\mu\nu} = \sum_{(\alpha)} T^{(\alpha)}_{\mu\nu} \text{ and } \nabla^\mu T_{\mu\nu} = 0 \text{ but } \nabla^\mu T^{(\alpha)}_{\mu\nu} = \underbrace{\sum_{(\beta)} Q_\nu^{(\alpha)\to(\beta)}}_{\text{interactions}}$$

$$Q_\nu^{(\alpha)\to(\beta)} = Q^{(\alpha)\to(\beta)}\, u_\nu + f_\nu^{(\alpha)\to(\beta)}$$

Energy transfer Momentum transfer

[K. Malik, D.Wands 2008]

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- Interactions between Kinetic and Potential fluids are set by the known e.o.m. for ϕ

$$a\bar{Q}_{K\to V} = -\phi' V_{\phi} \quad \text{and} \quad a\bar{Q}_{V\to K} = 0, \qquad \text{etc.}$$

Until now, just a different description for a single scalar field

[K. Malik, D.Wands 2008]

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- Add a third cosmological fluid f with e.o.s. w_f which interacts as

$$\boxed{\boldsymbol{Q^\mu_{K\to f} = \Gamma T^{\mu\nu}_K u^K_\nu}}$$

Choice of description of the microphysics
Covariant, non-perturbative

[K. Malik, D.Wands 2008]

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[J. Martin, T. Papanikolaou, L. Pinol, V. Vennin 2020]

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- But also for the perturbations (momentum transfer needed):

$$\delta\phi^{(\mathrm{gi})\prime\prime} + 2\mathcal{H}\delta\phi^{(\mathrm{gi})\prime} + \frac{a\Gamma}{2}\delta\phi^{(\mathrm{gi})\prime} - \nabla^2\delta\phi^{(\mathrm{gi})} + a^2 V_{\phi\phi}\delta\phi^{(\mathrm{gi})} = 4\phi'\Phi' - 2a^2 V_\phi \Phi - \frac{a\Gamma}{2}\phi'\Phi. \quad (3.23)$$

Not just the naive modification expected from the background one

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- And for the fluid (background + energy and velocity perturbations)

$$\rho_f' + 3\mathcal{H}(1 + w_f)\rho_f - \frac{\Gamma}{2a}\phi'^2 = 0, \qquad \text{etc.}$$

Sourced by the decays of the inflaton

COUPLING THE INFLATON

TO A COSMOLOGICAL FLUID

[J. Martin, T. Papanikolaou, L. Pinol, V. Vennin 2020]

Set of equations that can be consistently solved numerically

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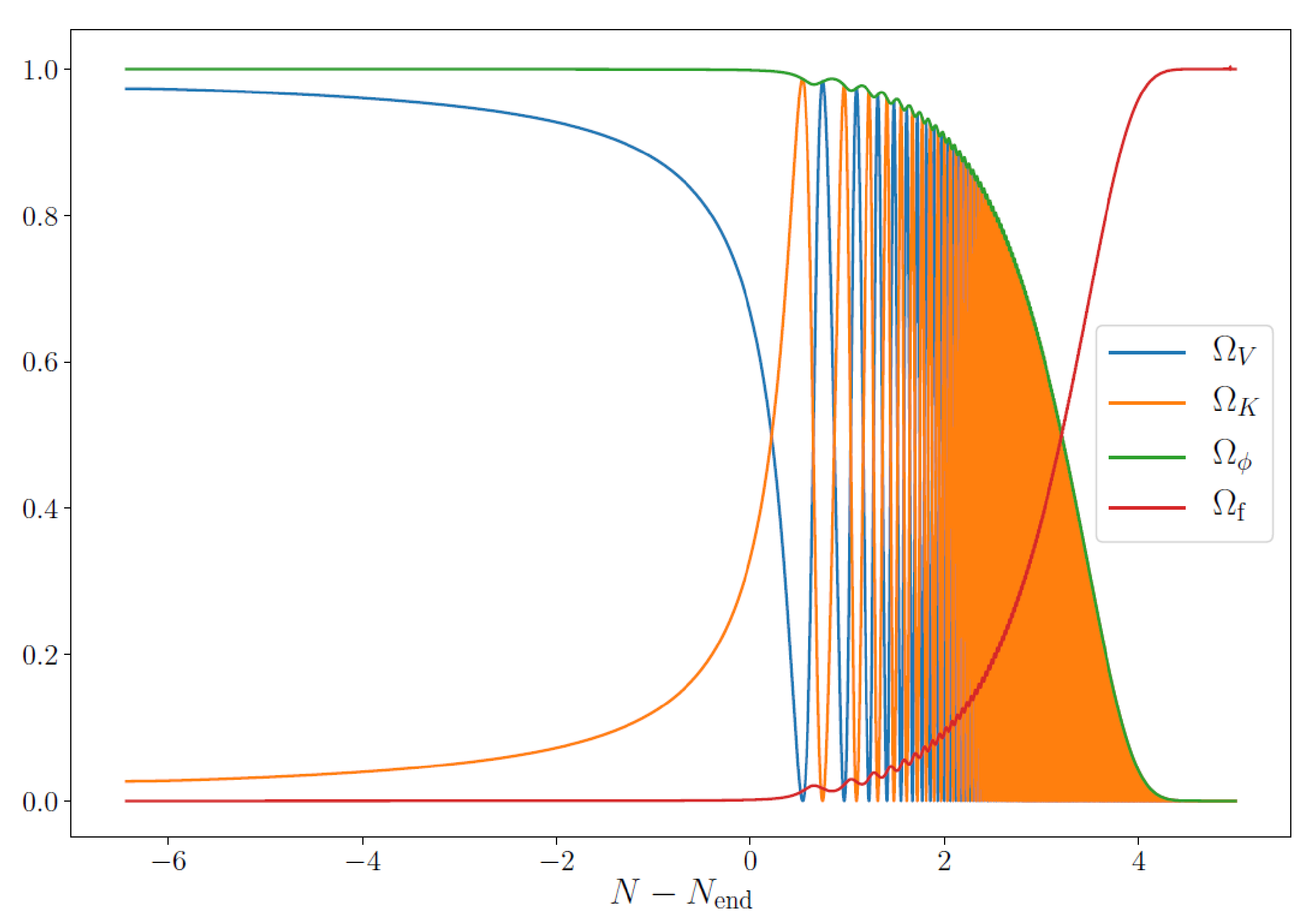
COUPLING THE INFLATON

TO A RADIATION FLUID

[J. Martin, T. Papanikolaou, L. Pinol, V. Vennin 2020]

$$\Omega_{(\alpha)} = \rho_{(\alpha)}/\rho_{\text{tot}}$$



We choose here:

- $V(\phi) = \frac{1}{2} m^2 \phi^2$, with $m = 10^{-5} M_p$
- $w_f = \frac{1}{3}$
- $\Gamma = 10^{-7} M_{\text{p}}$

Background energy transferred from inflaton to radiation

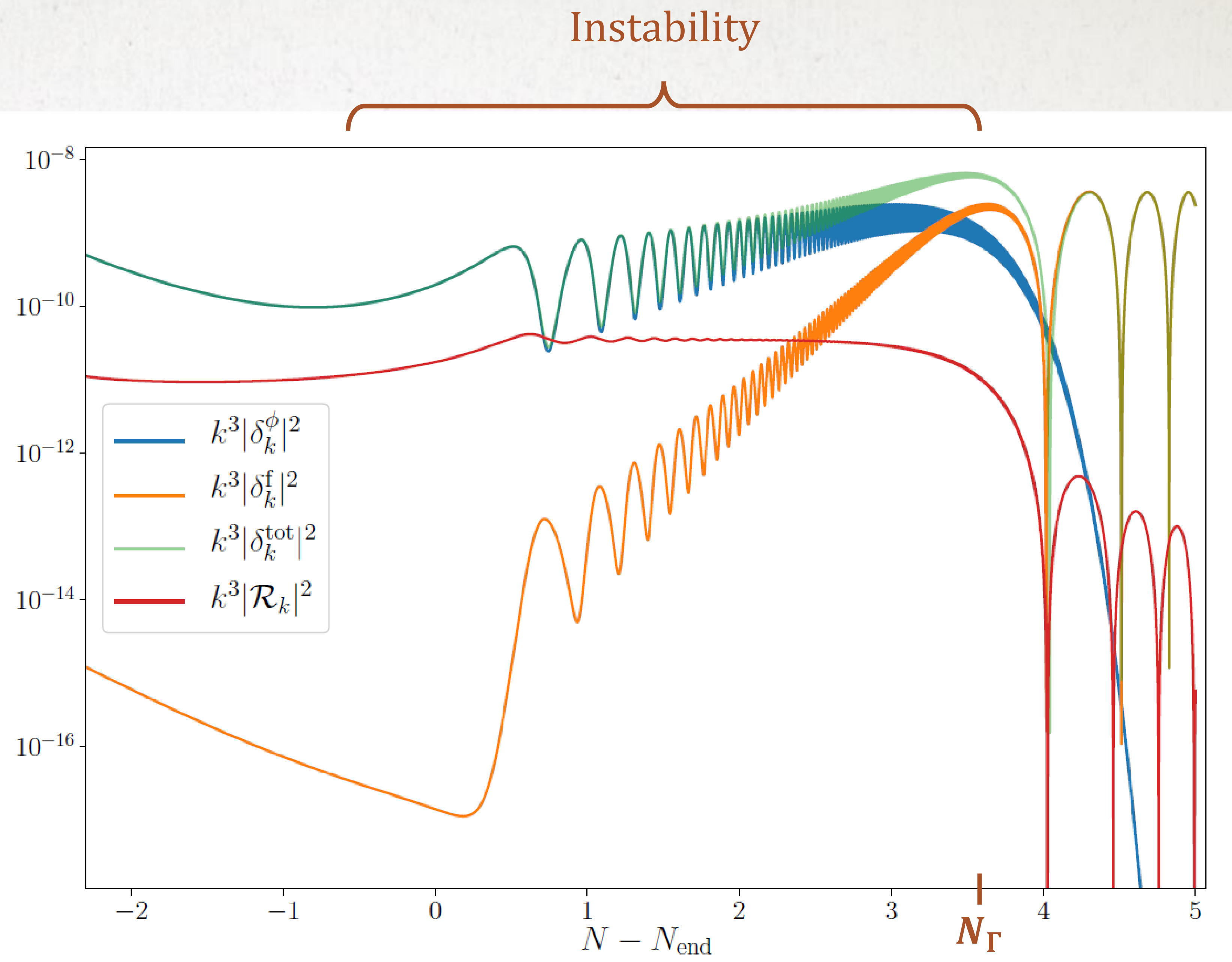
COUPLING THE INFLATON

TO A RADIATION FLUID

Perturbations

[J. Martin, T. Papanikolaou, L. Pinol, V. Vennin 2020]

- Scalar field density contrast still unstable and exponentially growing during oscillations
- Instability stops around N_Γ when $H(N_\Gamma) \sim \Gamma$ as expected
- Continuous transition to radiation-domination (background+perturbations)



COUPLING THE INFLATON

TO A RADIATION FLUID

[J. Martin, T. Papanikolaou, L. Pinol, V. Vennin 2020]

Claims in the litterature that:

Single, perfect fluid sytem

- Oscillations phase = pressureless perturbations in a matter-dominated Universe
- Effective equation of state $w_{\mathrm{eff}} = \frac{w_f}{2w_f + 1} \frac{2}{9} \frac{\Gamma}{H} \ll 1$ during the oscillations
- Then used to predict abundance of PBHs due to deviation from $w = 0$

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Many mistakes and in particular:

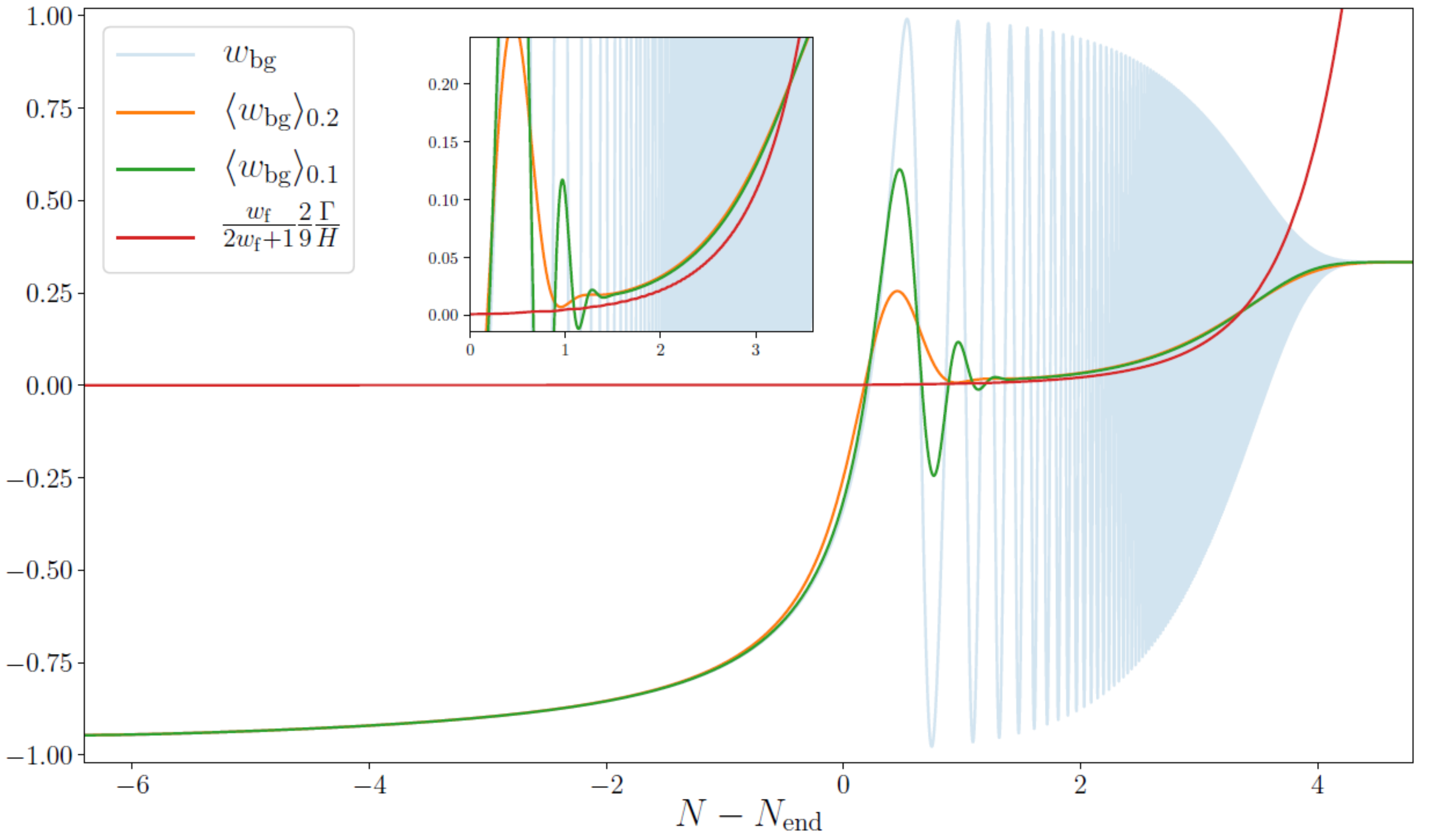
- Approximation for w not accurate for a long time
- $w_{\mathrm{background}} \neq w_{\mathrm{perturbations}}$

COUPLING THE INFLATON

TO A RADIATION FLUID

[J. Martin, T. Papanikolaou, L. Pinol, V. Vennin 2020]

- w_{eff} forgets about oscillations
- The time scale of averaging is crucial
- w_{eff} is not accurate while PBH production is highly sensitive to it



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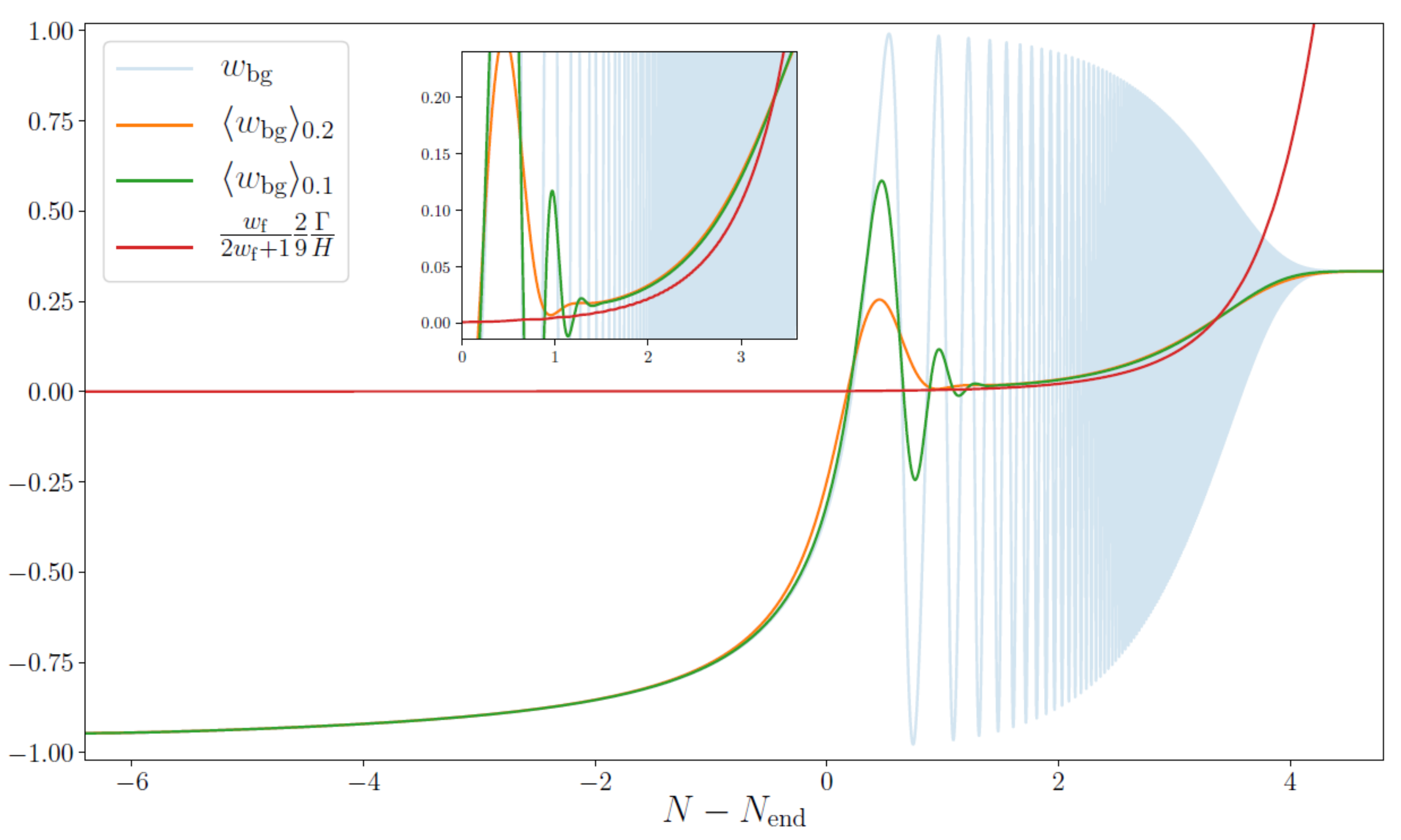
Metric preheating cannot be understood as single perfect fluid system



CONCLUSION

- Metric preheating is a linear instability for small scales during oscillations after inflation
- It can be understood with the formalism of Mathieu equations and Mathieu charts
- It leads to the generation of secondary GWs and formation of PBHs
- PBHs are copiously produced in this generic mechanism, which places constraints on reheating
- Perturbative reheating with decays of the inflaton to cosmological fluids does not spoil the instability
- Preheating and reheating together are complex phenomena and cannot be oversimplified

THANKS FOR YOUR ATTENTION!